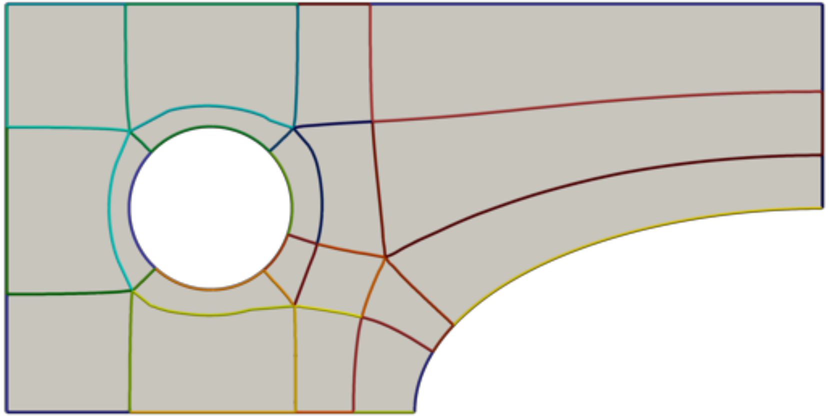
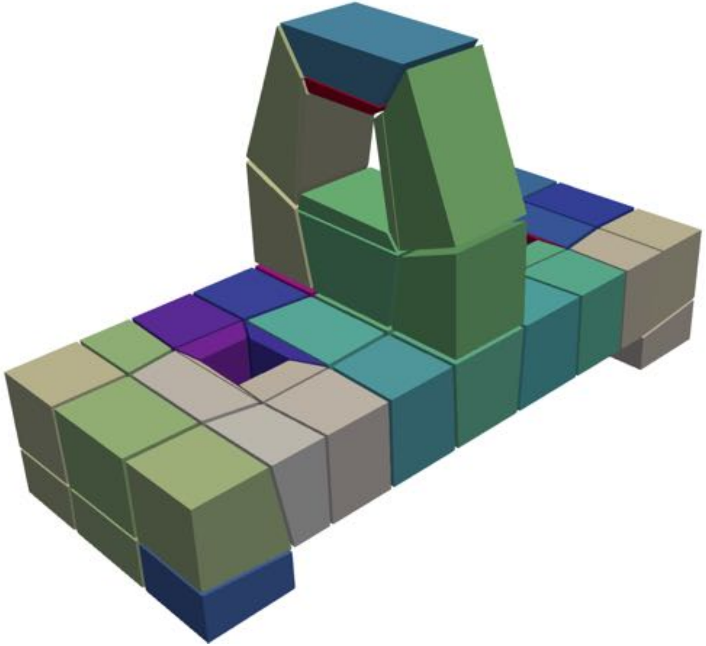
Bringing frame fields from research to industrial usage

Franck Ledoux

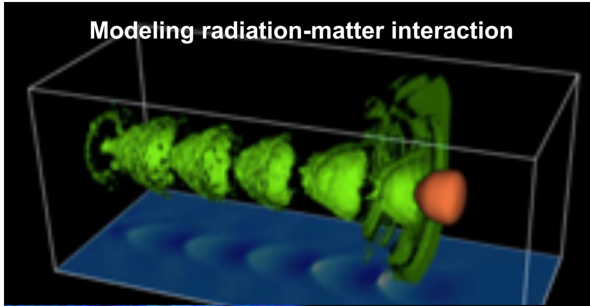


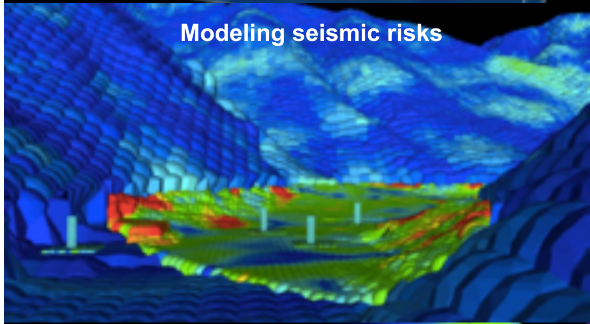


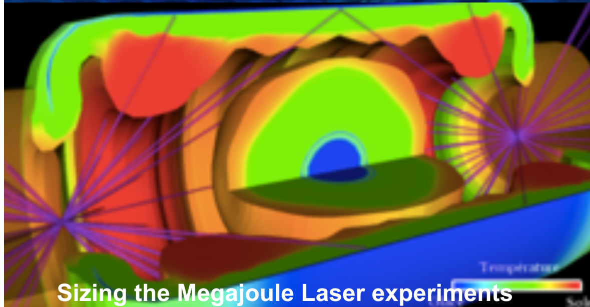
FRAMES 2019, July, 1-2 2019, Louvain-La-Neuve, Belgium

A quick presentation of my context (http://www-hpc.cea.fr/index-en.htm)

- **CEA is a French National Laboratory**
- *Focusing on research and development for energy solutions*
- *Participation in research and innovation for HPC* through the "Simulation Program" supported by its Direction des Applications Militaires(CEA / DAM).
- With software development including meshing tools
  - For CEA mathematicians and physicists
  - For French organisms we collaborate with





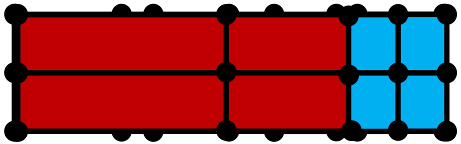


Meshes for numerical simulation

2(+1) main types of simulations

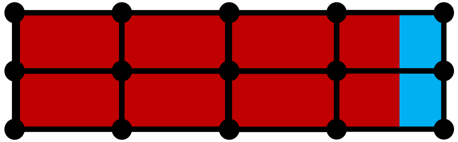
LAGRANGE

- **Moving meshes**
- **Pure material cells** and moving vertices
- |Cells| = Millions to hundred of millons



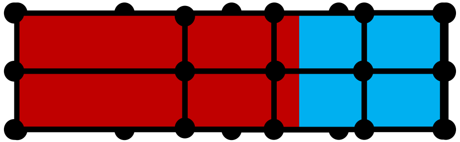
EULER

- **Static meshes** with possibly local refinement (AMR)
- **Mixed-material cells**
- |Cells| = dozens of millions to billions



ALE

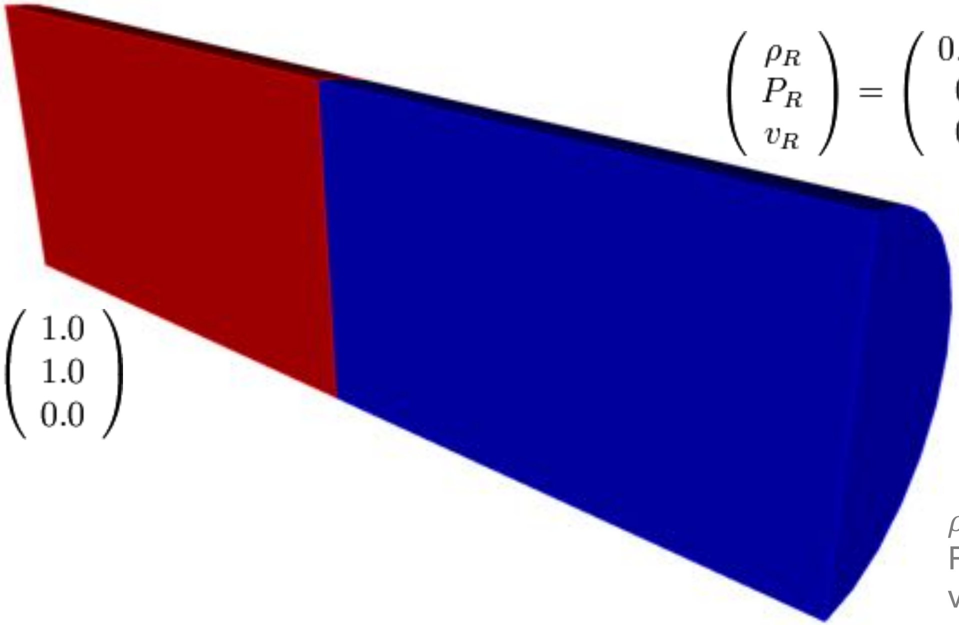
- Adaptive Lagrange Euler
- Moving mesh and mixed-material cells
- But movement is controled by the numerical code



Meshing for Lagrange Hydrodynamics code – Sod use case

The Sod shock tube problem 1-dimensional Riemann problem, with the following parameters for an ideal gaz

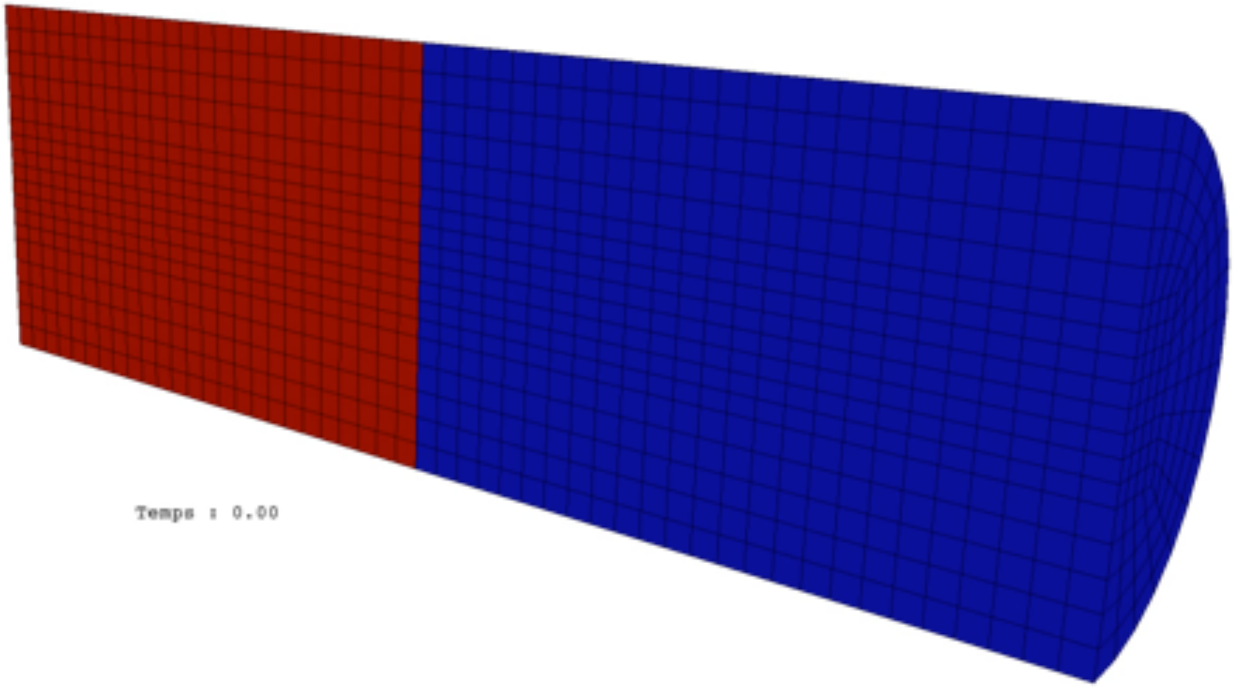
$$\begin{pmatrix} \rho_R \\ P_R \\ v_R \end{pmatrix} = \begin{pmatrix} 0.125 \\ 0.1 \\ 0.0 \end{pmatrix}$$



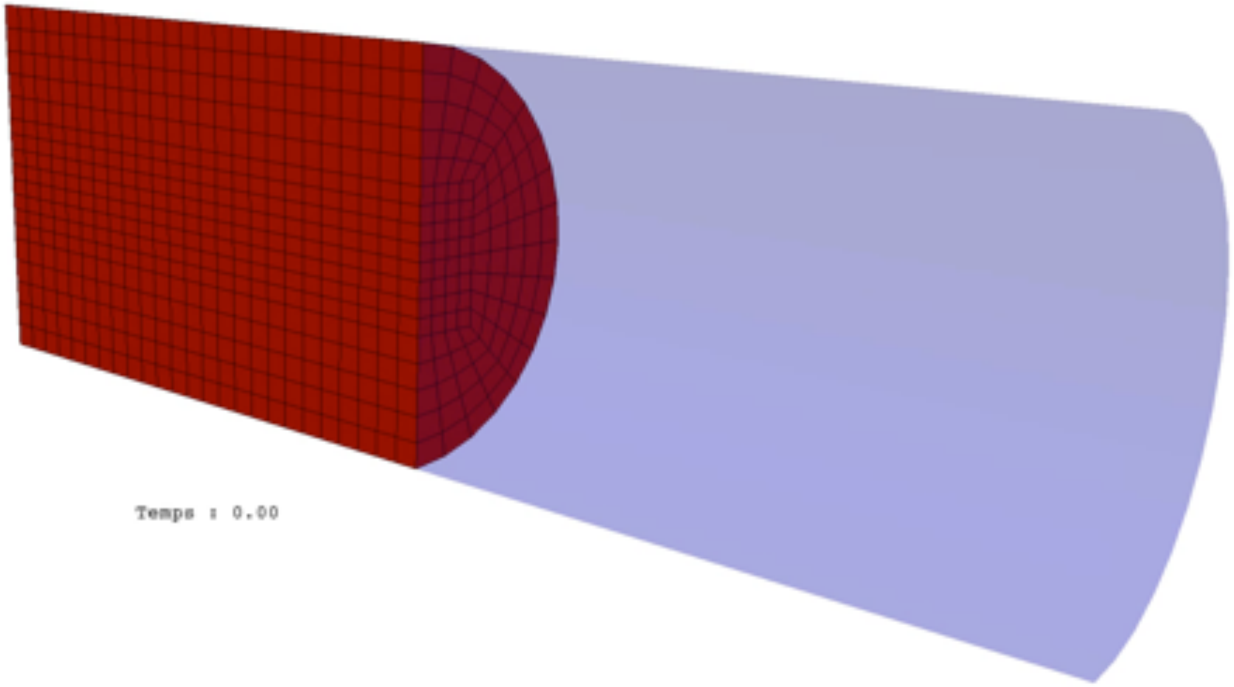
$$\begin{pmatrix} \rho_L \\ P_L \\ v_L \end{pmatrix} = \begin{pmatrix} 1.0 \\ 1.0 \\ 0.0 \end{pmatrix}$$

ρ is the density
P is the pressure
v is the velocity

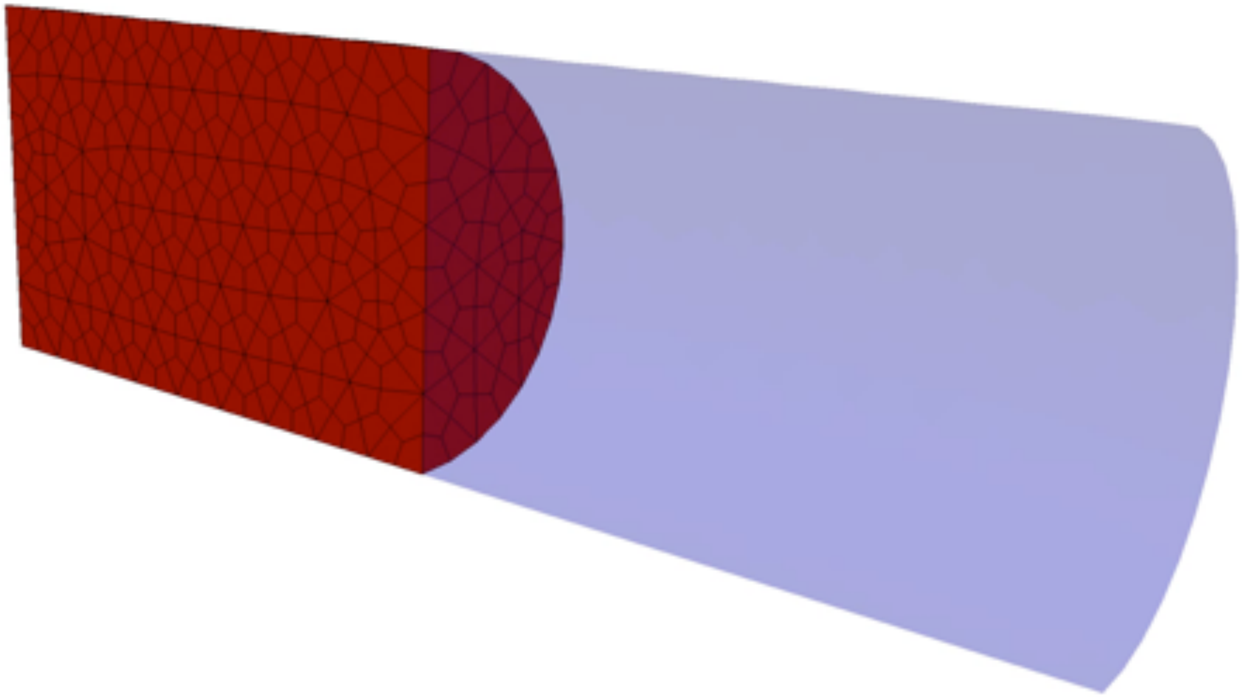
Meshing for Lagrange Hydrodynamics code – Sod use case



Meshing for Lagrange Hydrodynamics code – Sod use case



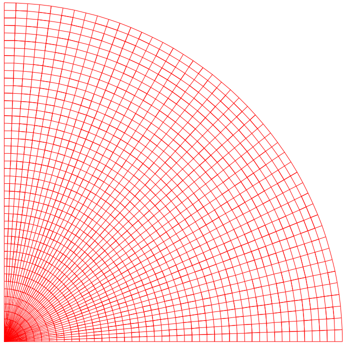
Meshing for Lagrange Hydrodynamics code – Sod use case

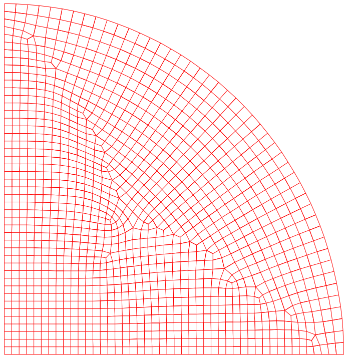


Meshing for Lagrange Hydrodynamics code – Sedov use case

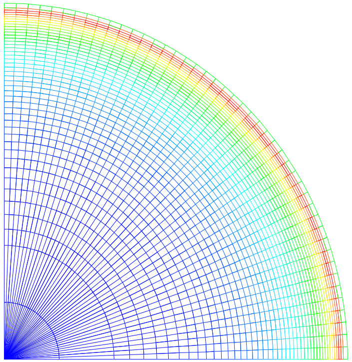
Propagation of a spherical shock wave from a point source energy (sphere center).

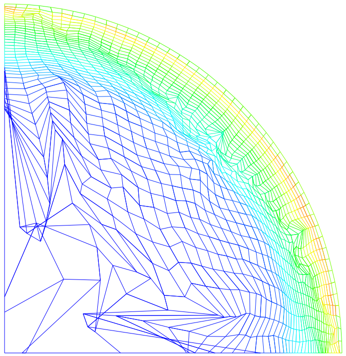
Two meshes of the same domain filled of gaz



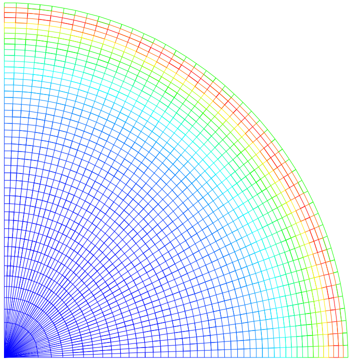


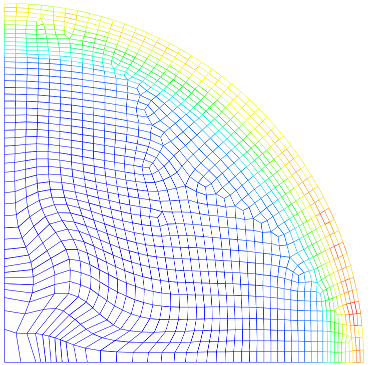
LAGRANGE STRATEGY





ALE STRATEGY

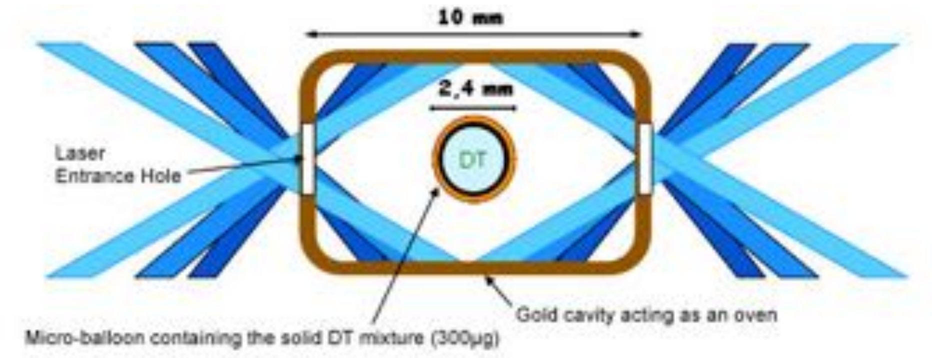




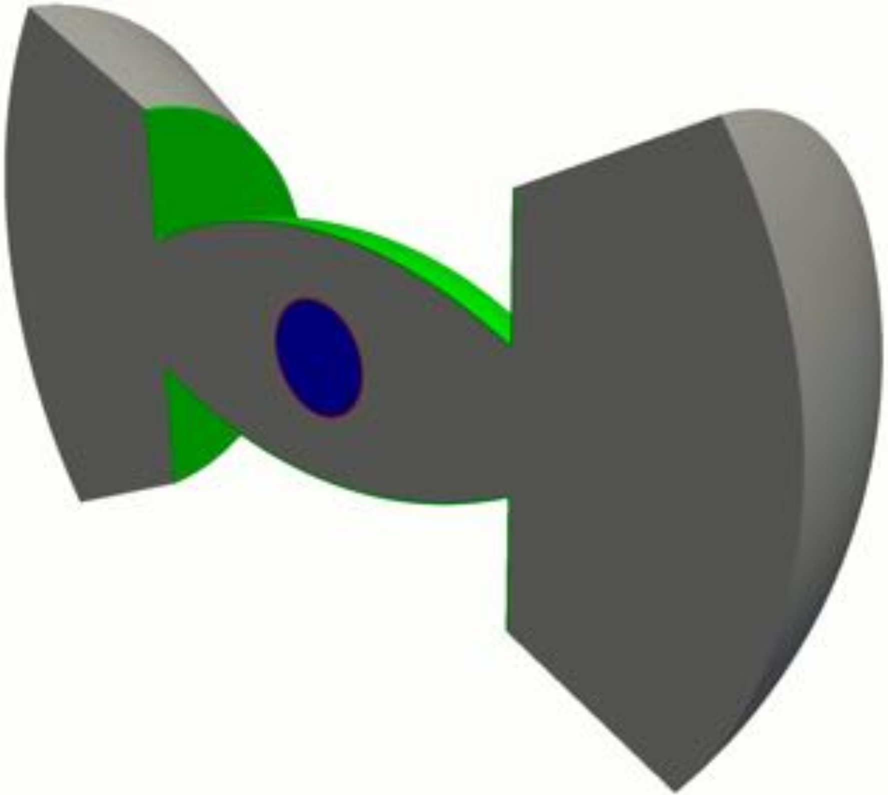
Megajoule Laser Experiments (http://www-lmj.cea.fr/)

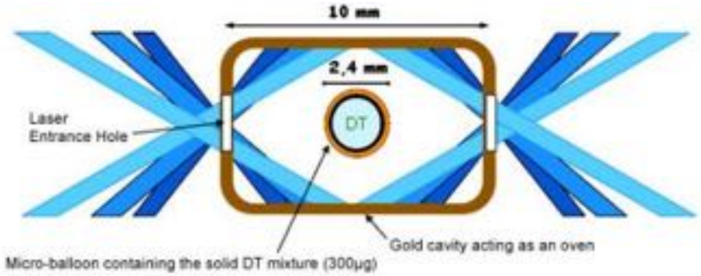
Goal: achieve inertial confinement fusion (ICF) through indirect drive with ignition of a central hotspot.

- Equivalent to the American National Ignition Facility (NIF) at LLNL
- The principle is to produce fusion reactions within a Deuterium-Tritium mixture contained in a microcapsule using powerful lasers. You get then a very dense plasma but only for very short periods of time.



Example of Lagrange simulation for LMJ experiences





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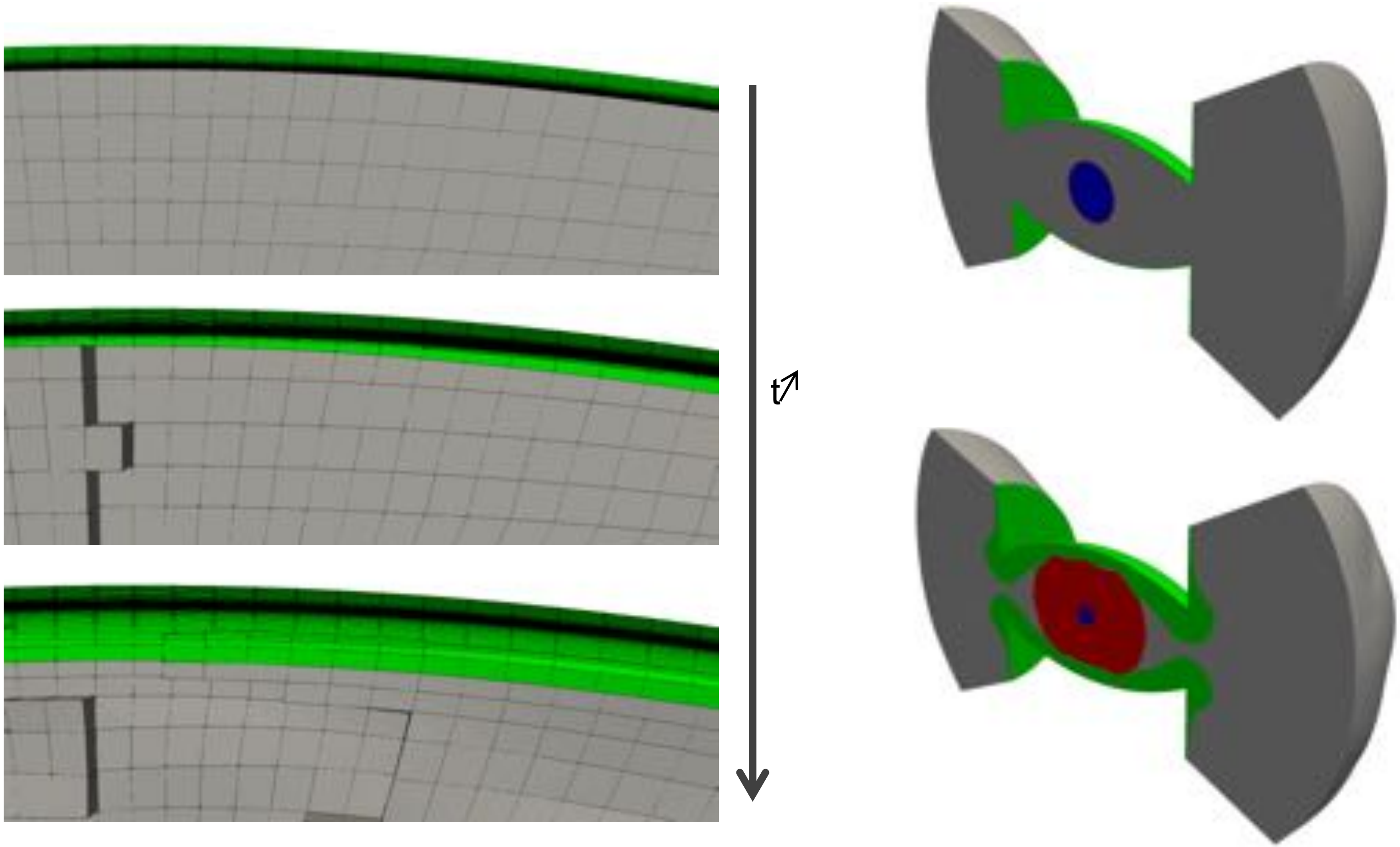

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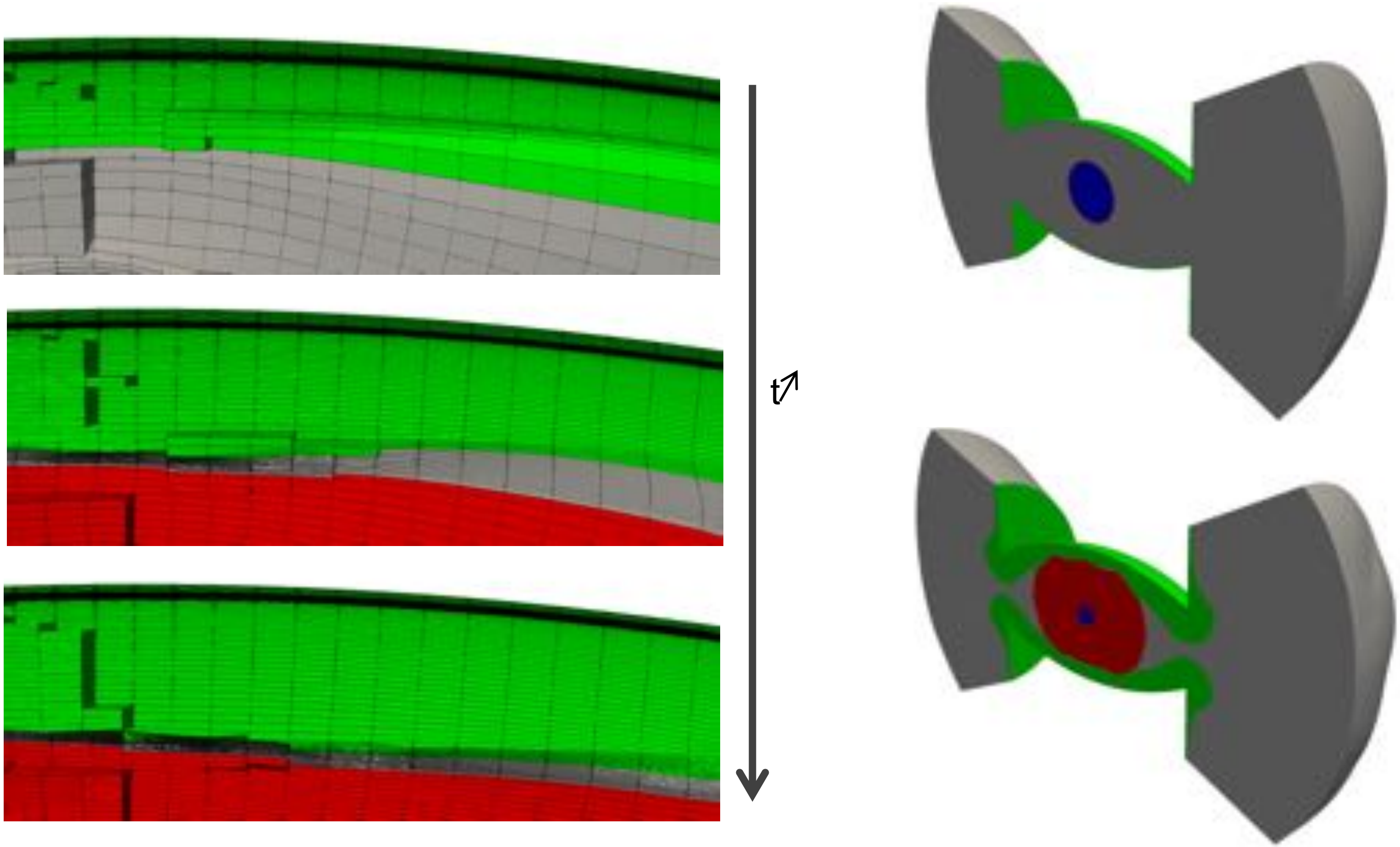

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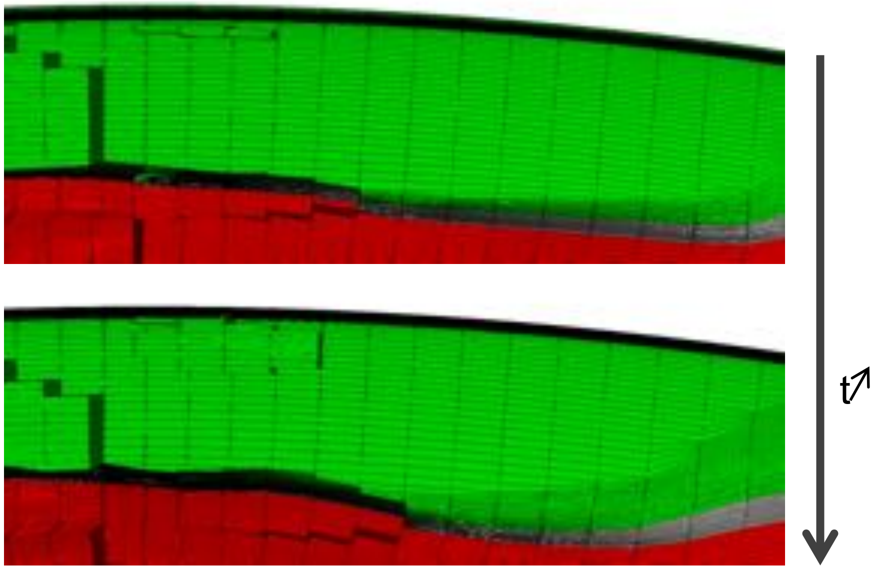
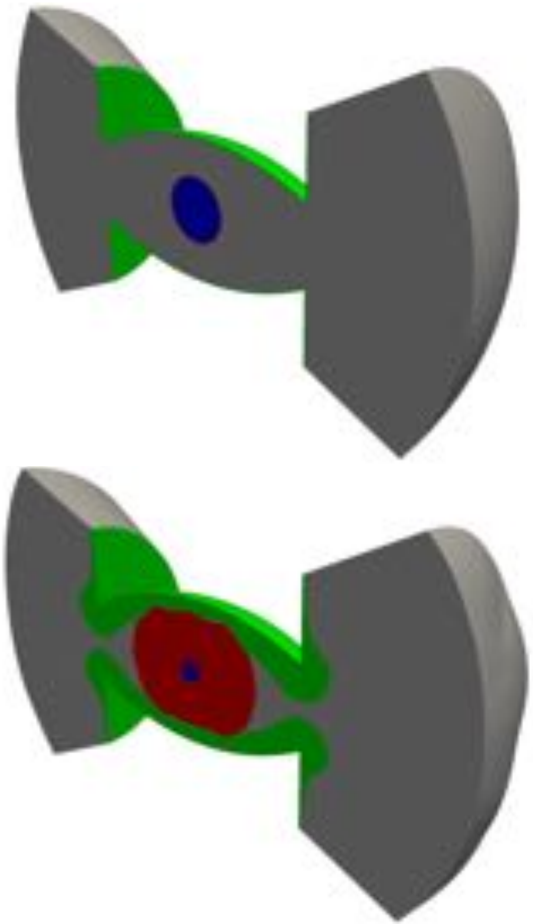
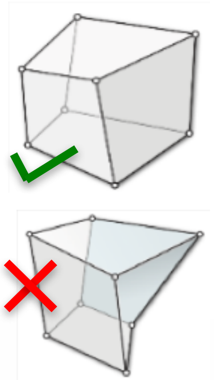




Lagrange simulations with large deformations

- Full hexahedral meshes
- Strong size and direction control

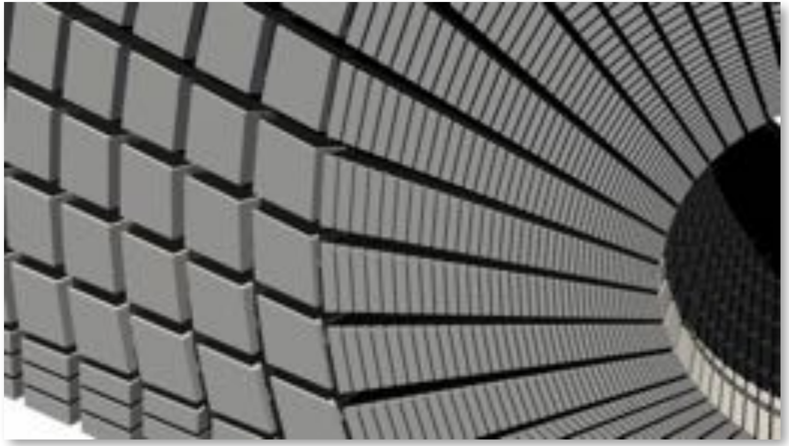
What do our users expect?

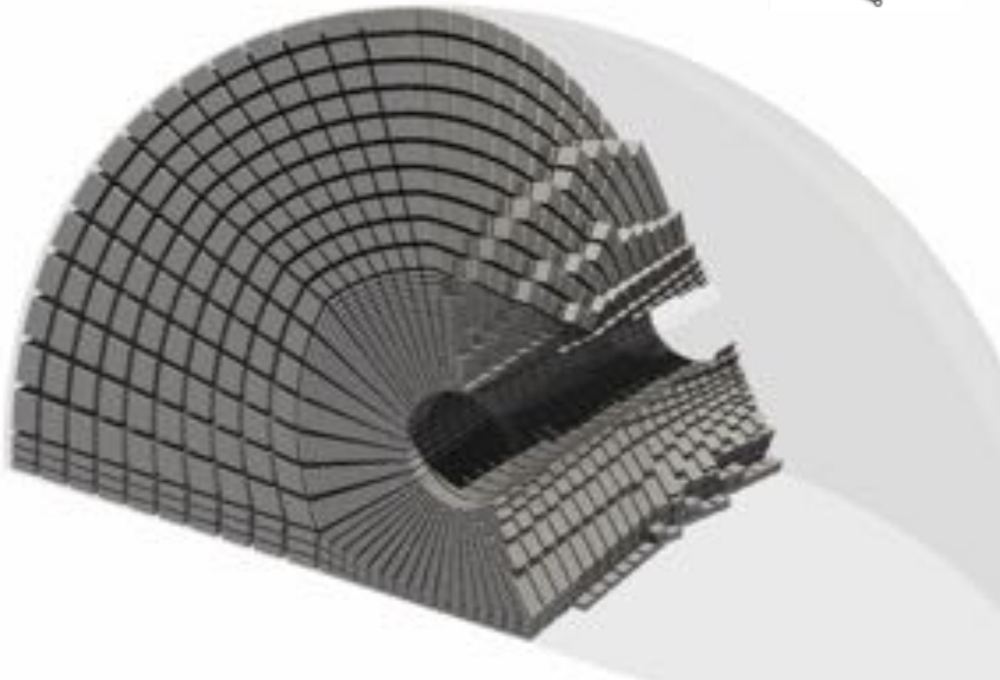


The mesh is a parameter that physicists want to control

- Depends on the simulation (physics and numerics concerns)
- But some usual expected features of hexahedral meshes

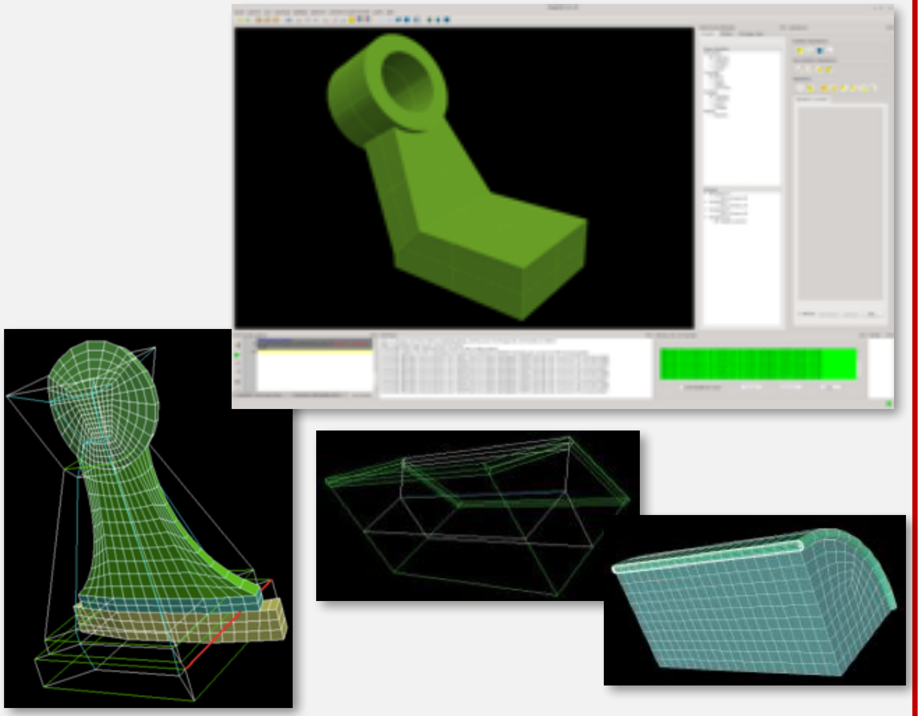
1. Block structure
2. Geometric boundary alignment
3. Low distortion of the cells
4. Element size control





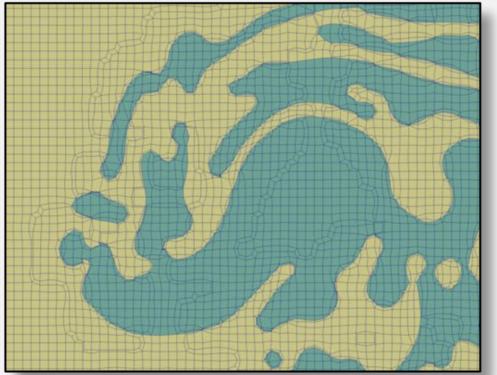
What we do for our users?

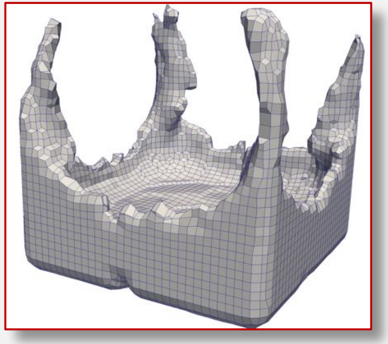
Software for CAD modeling and block-structured quad/hex meshing



Software for mesh processing

- Parallel mesh data structure
- Parallel meshing
- Quantity projection
- Euler to Lagrange remeshing





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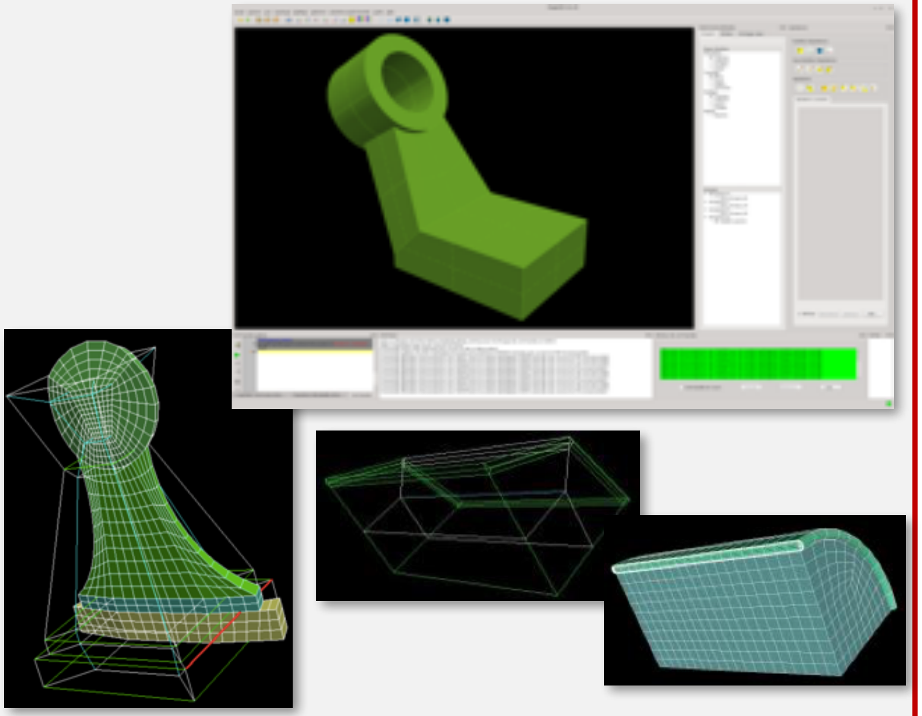


Can we bring frame field results from research to our tools?

Outline

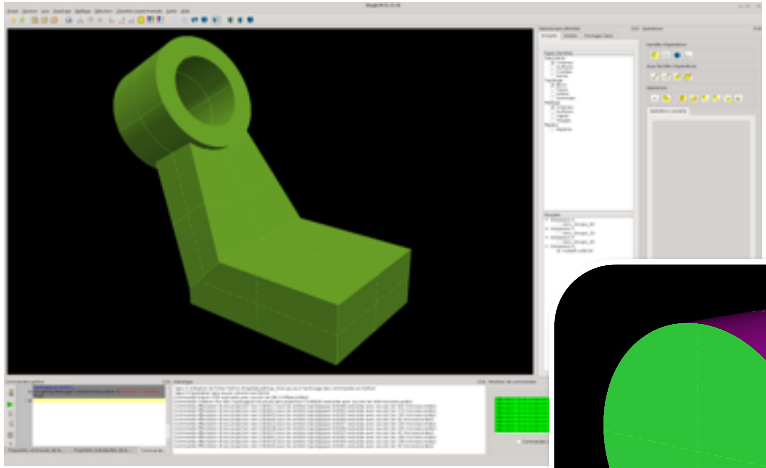
- Magix3D - CEA tool dedicated to hexahedral block meshing
- *Frame field research at CEA from 2013*
- *On-going works for bringing frame field technology to our users*
  - 2D cross fields
  - 3D frame fields

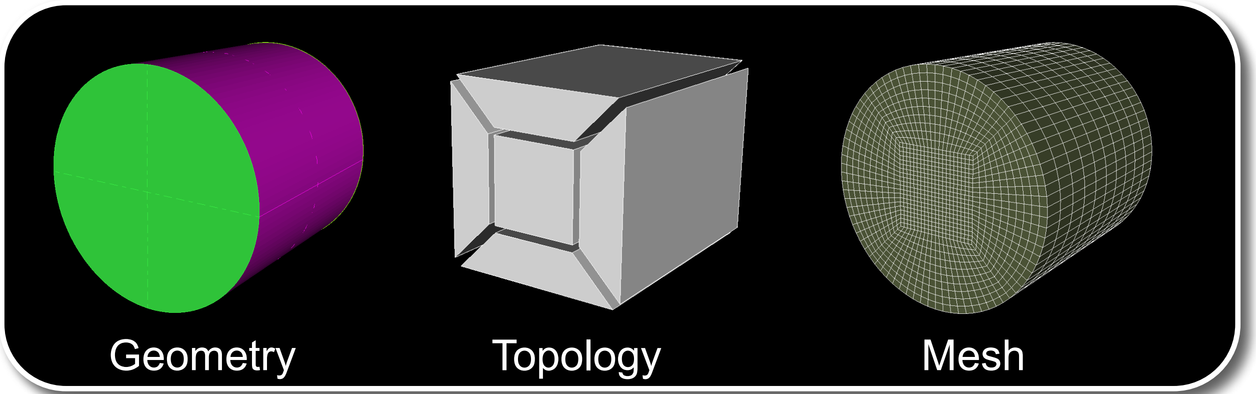
MAGIX3D

A tool dedicated to hexahedral block meshing

Magix3D – A tool dedicated to hexahedral block meshing

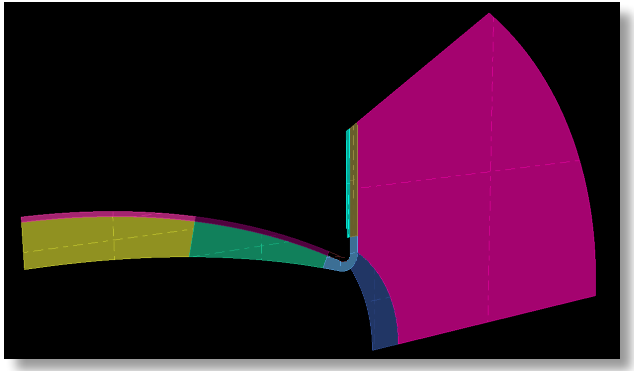
- Tailored to physicists requirements, who want to control the meshing process
- Simple geometric functionalities and advanced hex meshing capabilities
- 3 launch modes: station, client-server and batch

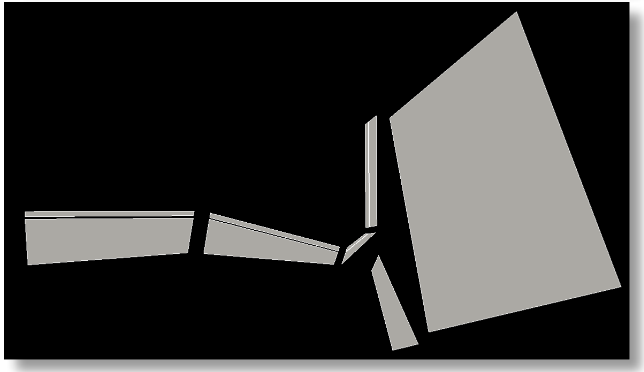


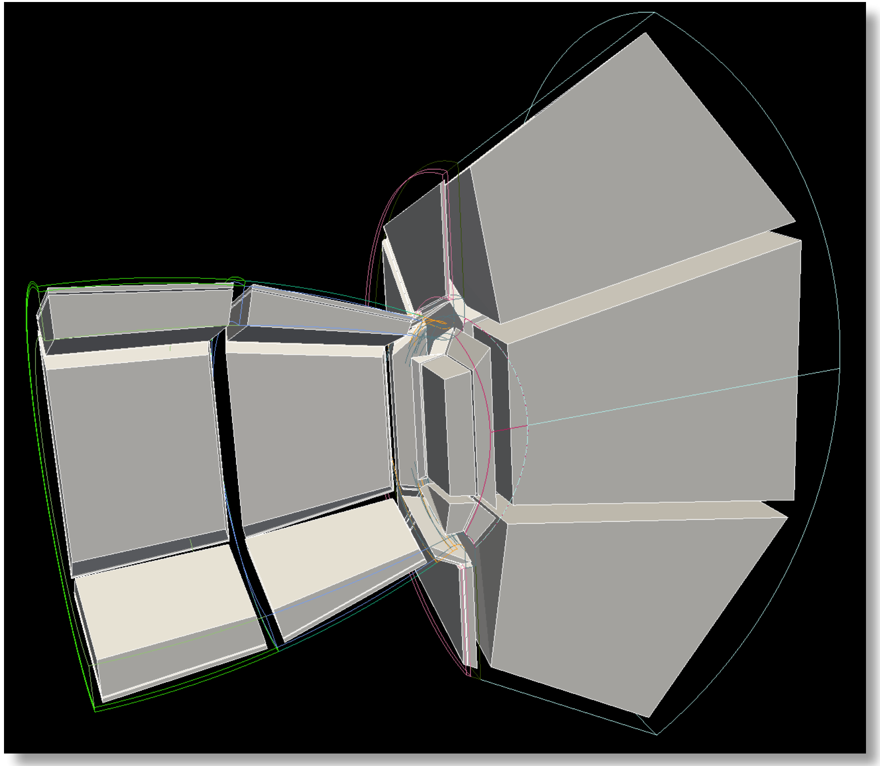


Magix3D – A tool dedicated to hexahedral block meshing

- 2D to 3D capabilities

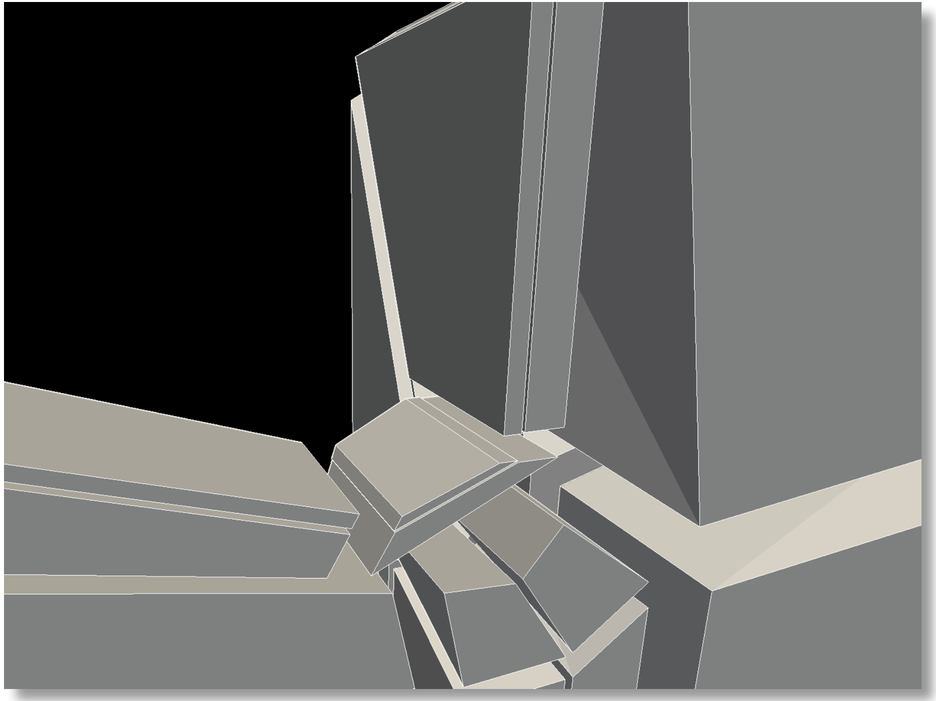




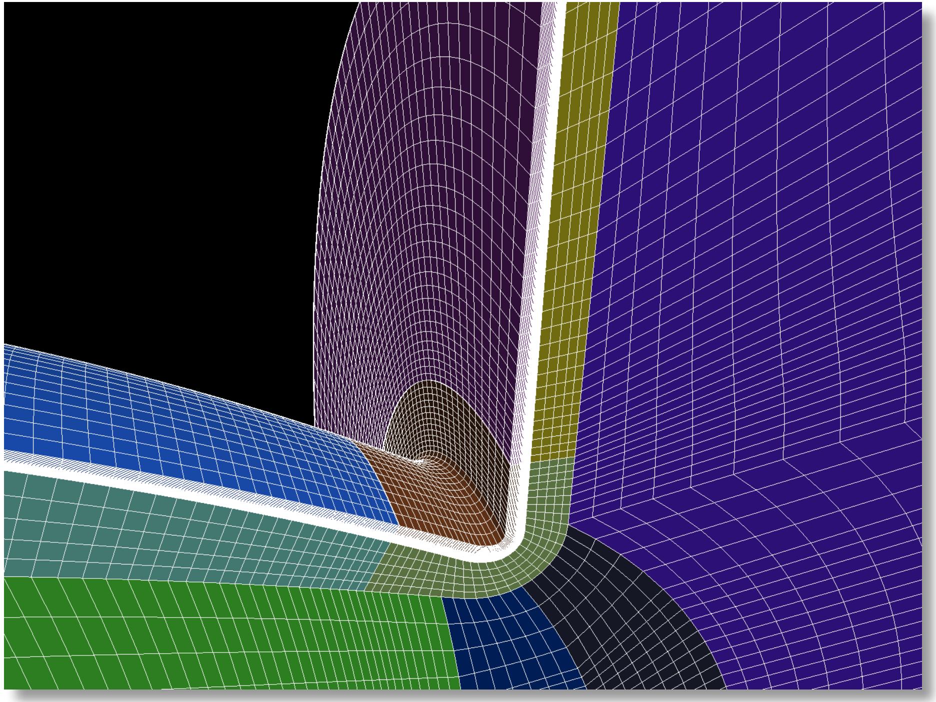


Magix3D – A tool dedicated to hexahedral block meshing

- Non-conforming blocking

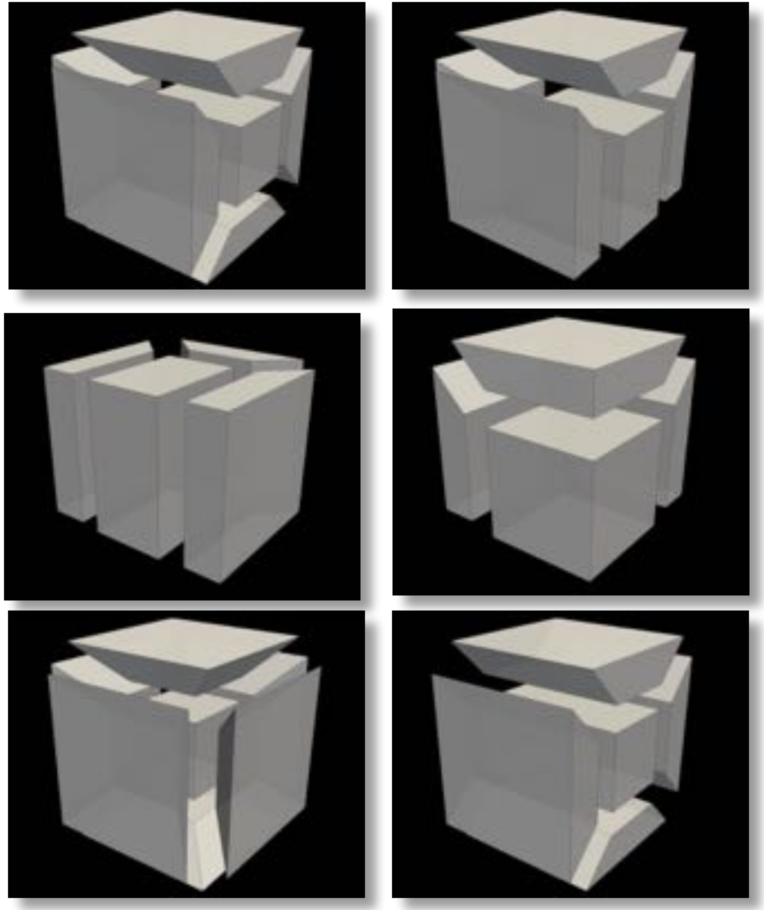


- Size control

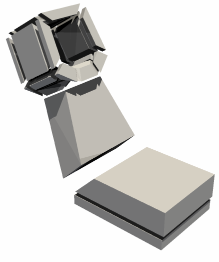
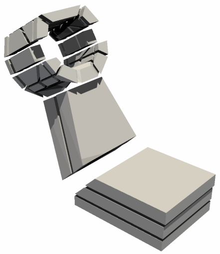
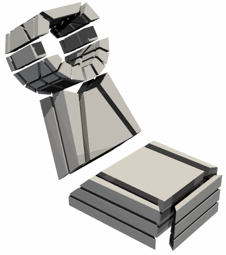


Magix3D – A tool dedicated to hexahedral block meshing

- Blocking operations
  - Single block creation
  - Multi-block cutting
  - Multi-block splitting via O-grid patterns
  - Geometric classification
  - Smoothing



A simple CAD model with Magix3D

Model						
Block Structure						
|B|	29 blocks	59 blocks	62 blocks	92 blocks	132 blocks	174 blocks
Average time	15 mins	25 mins	30 mins	1 hour	1.5 hours	2 hours

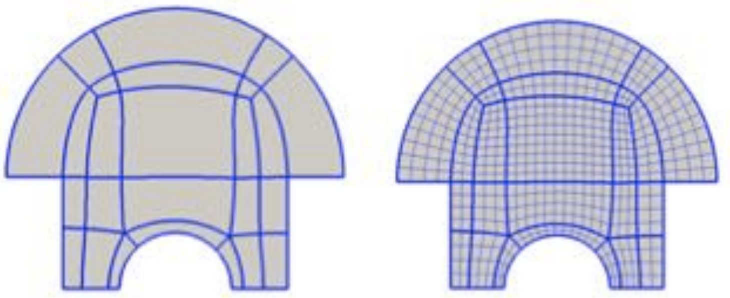
Can our meshing research help us?

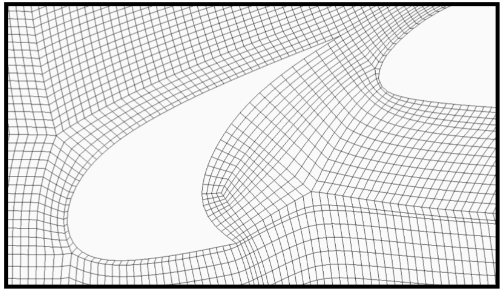
Frame fields at CEA – since 2013

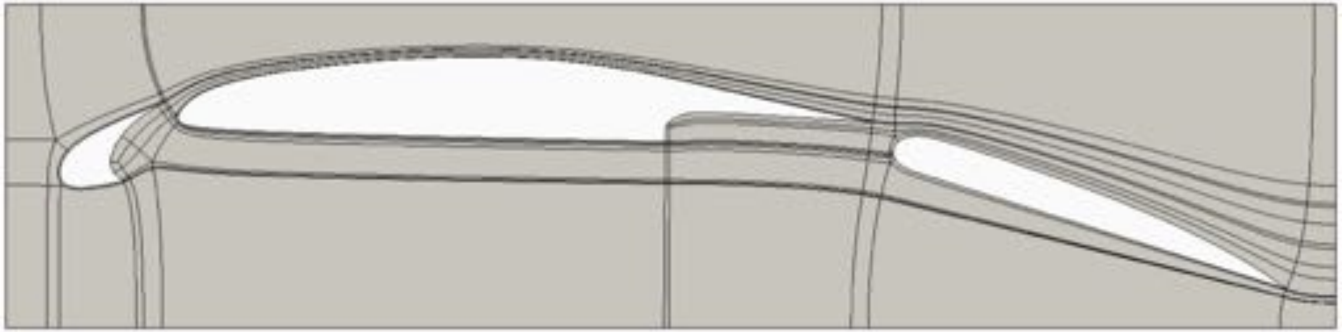
Nicolas Kowalski's PHD.
Domain partitioning using frame fields: applications to quadrilateral and hexahedral meshing.
Defended in 2013. Advisors P. Frey (UPMC) & F. Ledoux (CEA)

Generation of full-quad structured meshes in 2D

- Hexahedral block structure appears
- Only 3 and 5-valence vertices
- **Theoretical ground offers guarantees**







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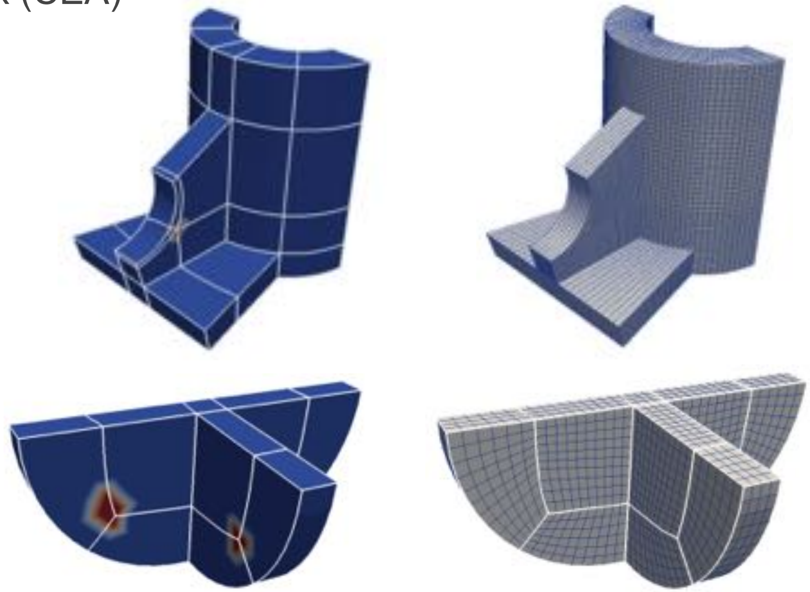
It didn't work in 3D

- No guarantee to get a block structure
- Numerically sensitive
- Limited to simple examples



[Huang et al. 11] Jin Huang, Yiying Tong, Hongyu Wei, and Hujun Bao. Boundary aligned smooth 3d cross- frame field. ACM Trans. Graph., 30(6):143, 2011.

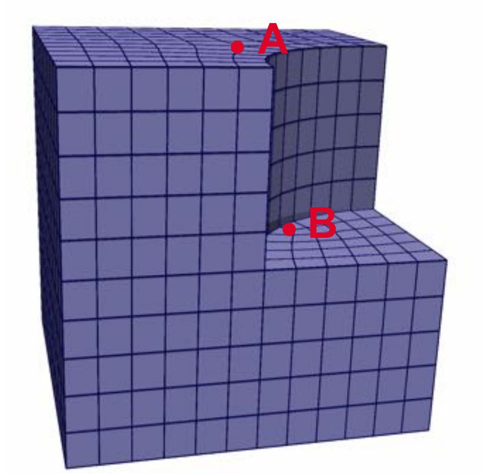
[Li et al. 12] Y. Li, Y. Liu, W. Xu, W. Wang, and B. Guo. All-hex meshing using singularity-restricted field. ACM Trans. Graph., 31(6):177:1–177:11, 2012.

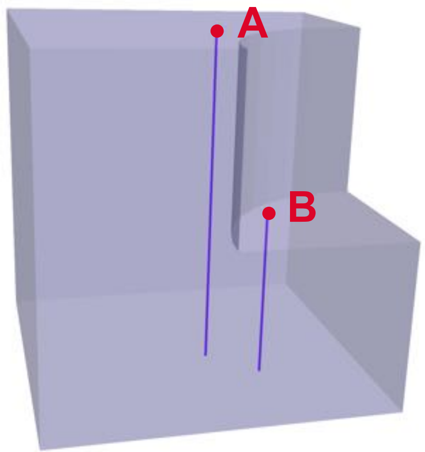
[Kowalski et al. 15] N. Kowalski, F. Ledoux, and P. Frey. Smoothness driven frame field generation for hexahedral meshing. *Computer Aided Design,* 2015.

Frame fields at CEA – since 2013

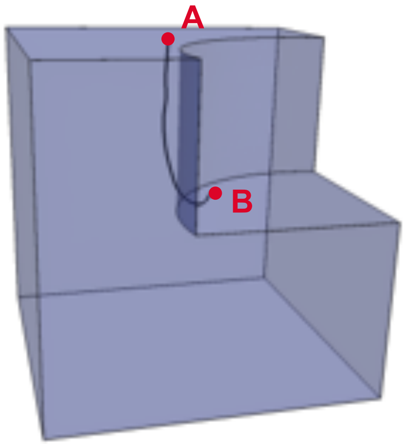
Try to make it work in 3D, still without any success

- 3-5 singularity lines





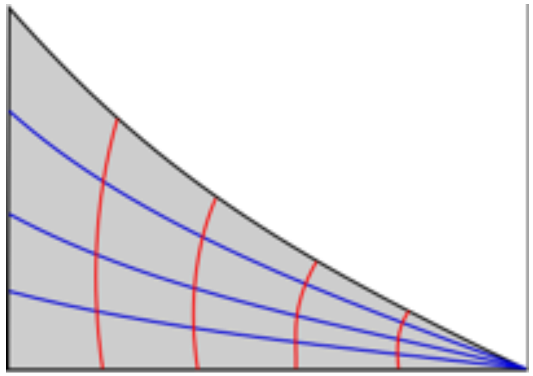
Extruded model along one linear direction



Singularity line in the generated frame field

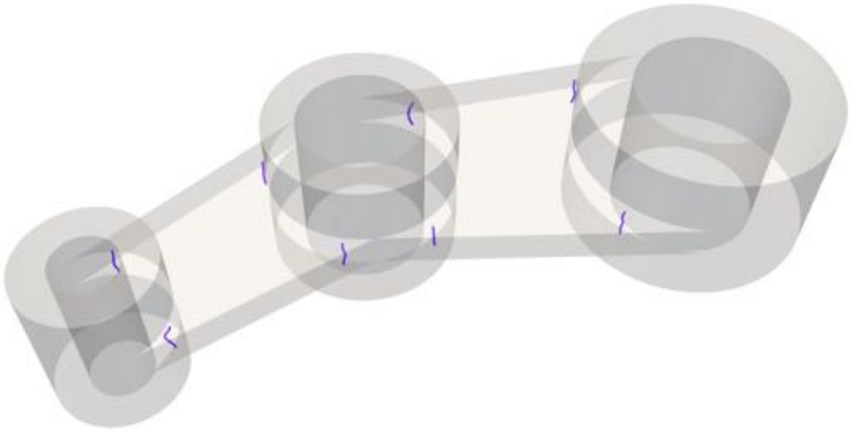
[Vie16] Ryan Viertel, Matt Staten and Franck Ledoux, Analysis of Non-Meshable Automatically Generated Frame Fields, research note at 25th International Meshing Roundtable, 2016.

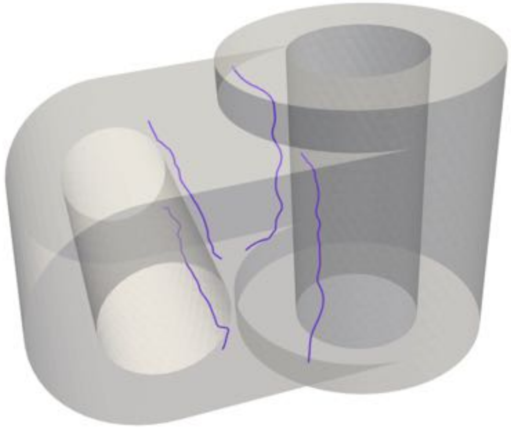
Frame fields at CEA – since 2013



Try to make it work in 3D, still without any success

- 3-5 singularity lines
- Ski jump configuration





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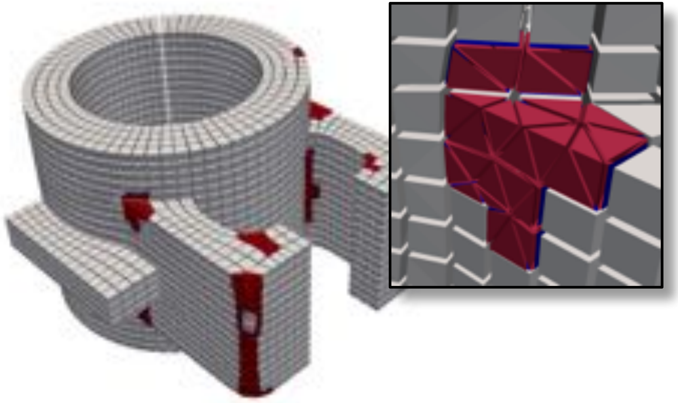
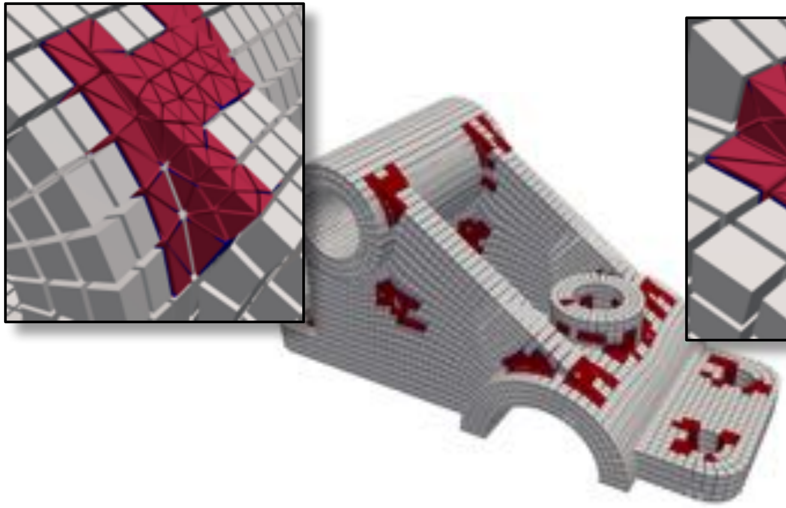
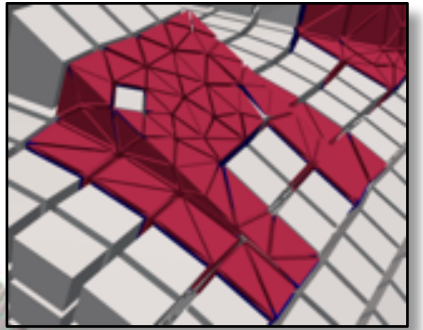
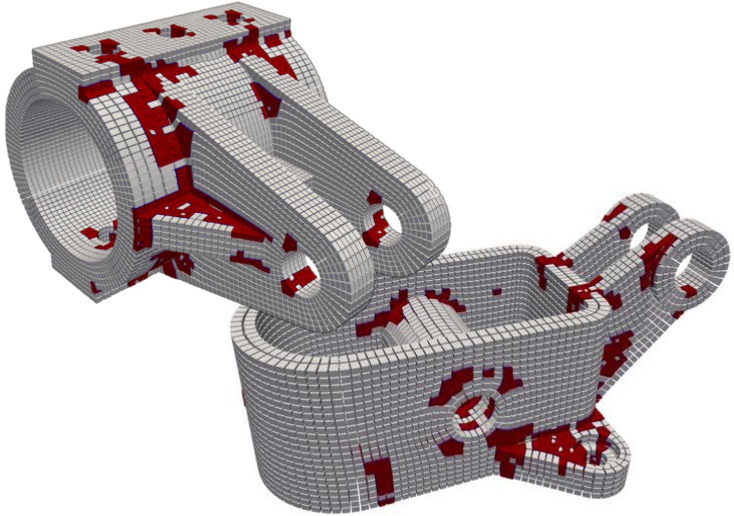


Try to make it work in 3D, still without any success

- 3-5 singularity lines
- Ski jump configuration
- **So we have relaxed to hex-dominant meshing** (but remains to control locality at least)



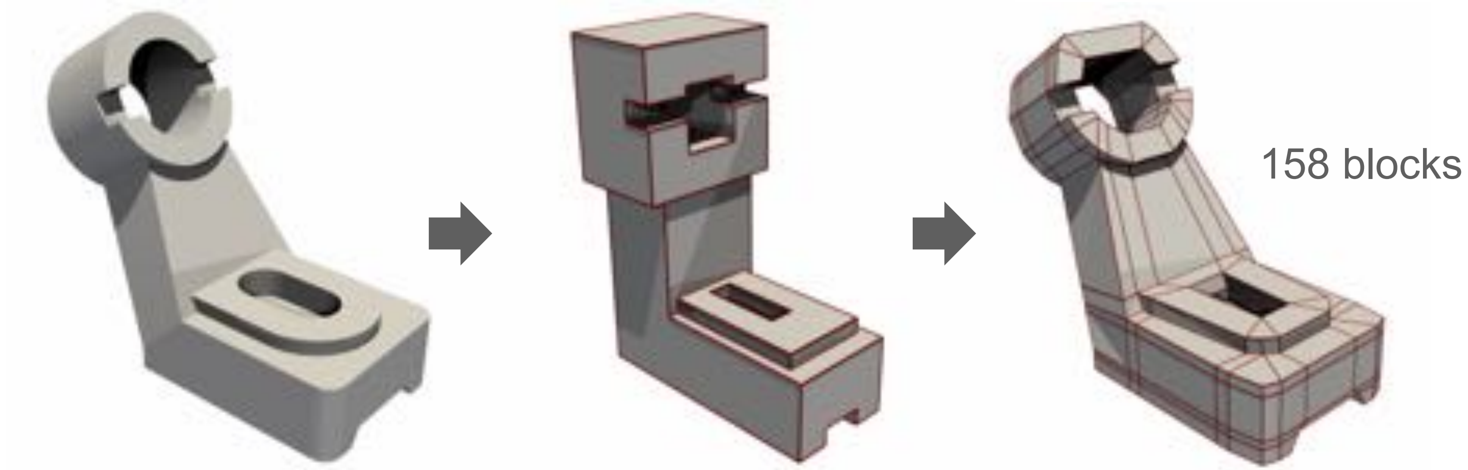




Frame fields at CEA – since 2013

Try to make it work in 3D, still without any success

- 3-5 singularity lines
- Ski jump configuration
- **So we have relaxed to hex-dominant meshing** (but remains to control locality at least)
- Took a look at Polycubes



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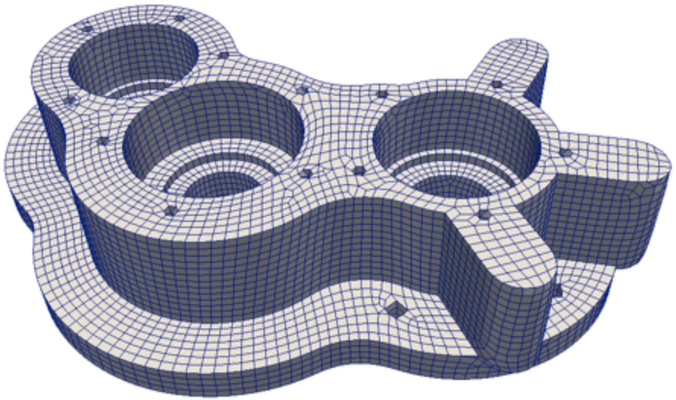

Try to make it work in 3D, still without any success

- 3-5 singularity lines
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- **So we have relaxed to hex-dominant meshing** (but remains to control locality at least)
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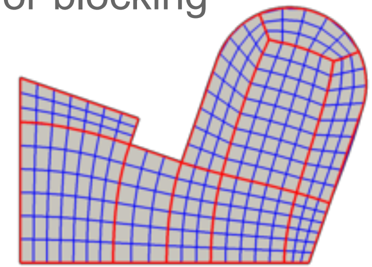
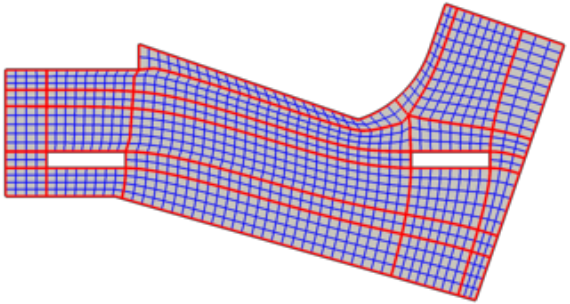
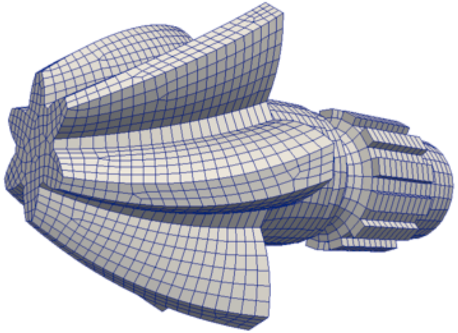
Try to put 2D results in our meshing software for surface meshing

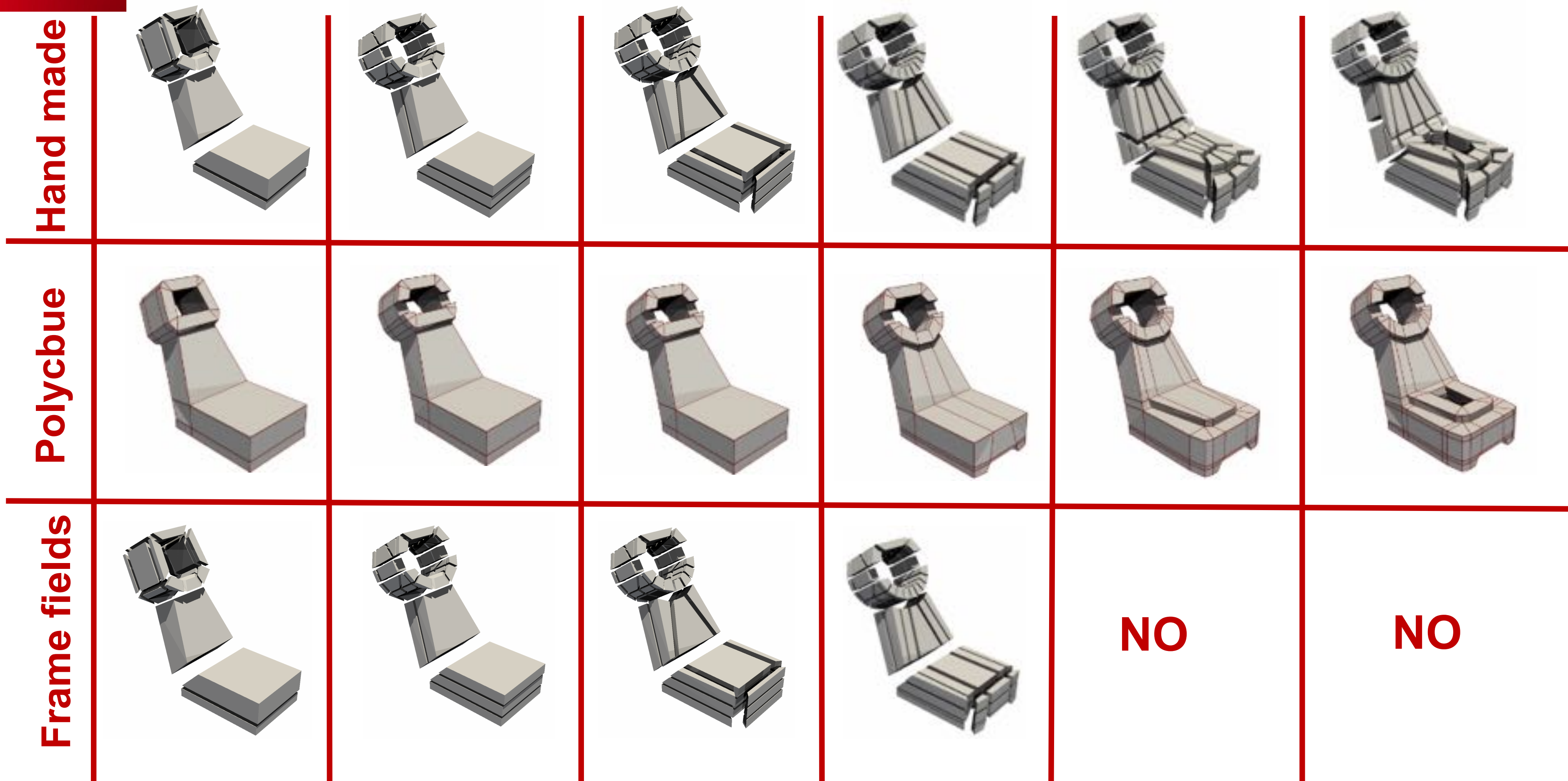
- For unstructured quad(-dominant) meshing via an indirect approach (idem work to do)
- For blocking







A simple CAD model with Magix3D, Polycube and Frame fields



Frame fields – Focus on failure cases

But what can we bring to the final users RIGHT NOW ?

2D Automatic meshing

- **Curved block structure**
- Unstructured full-quad with size control and boudary alignment

3D Blocking

- **3D interactive approach - Use frame field to define a new tool**
- Hex-dominant meshing – must be evaluated by users.

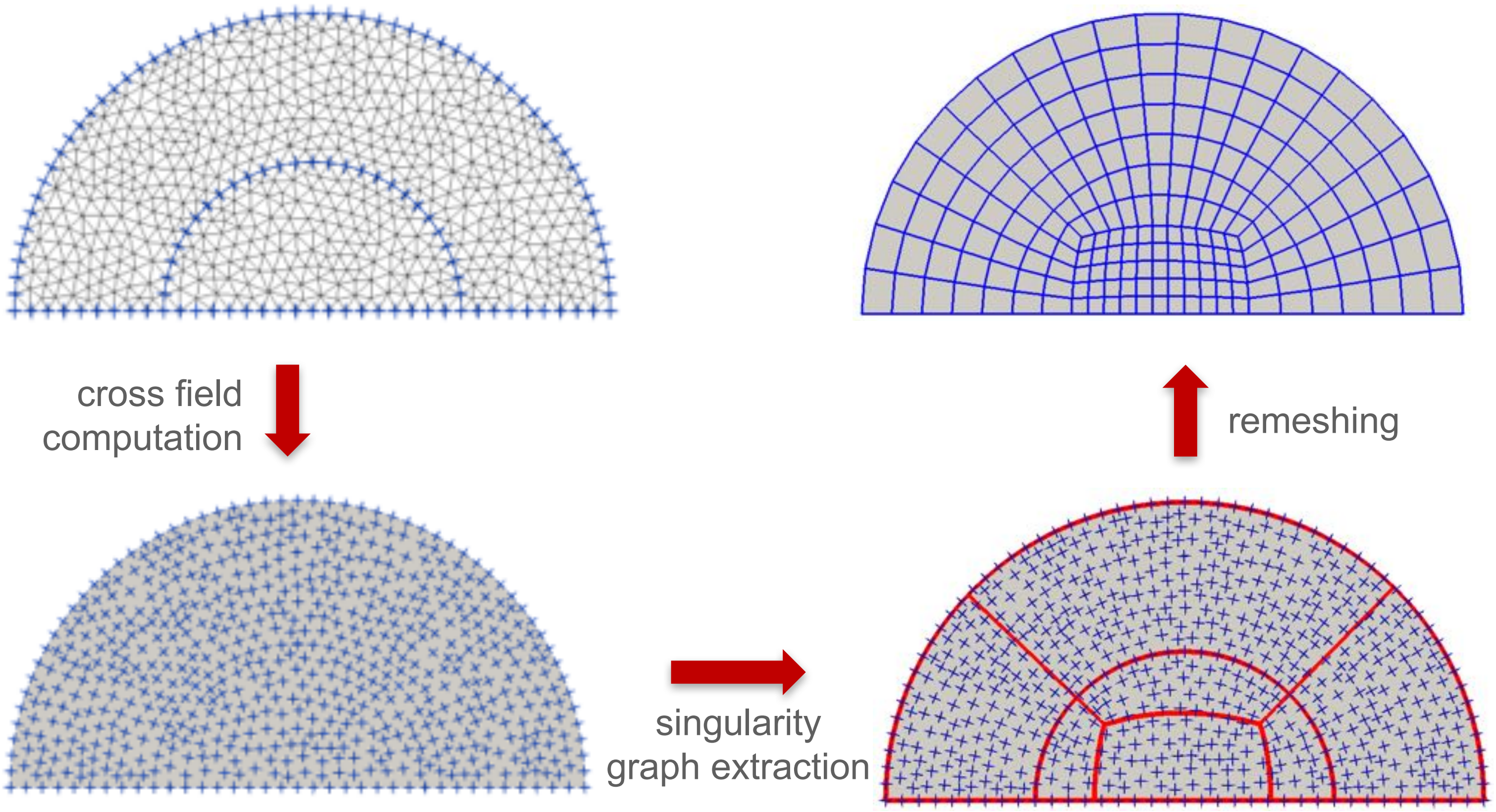
AND AFTER

- Polycube and frame fields studies

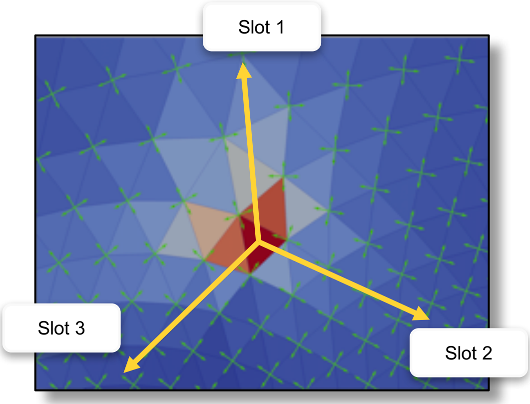
Towards a robust surface blocking method

Ana-Maria Vintescu’s Post-doc (since January 2019)

Frame fields for 2D block structure

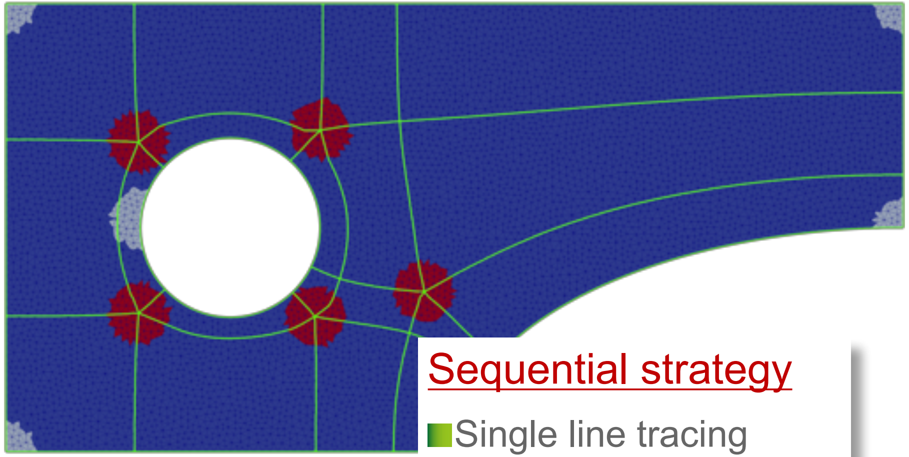


How to trace singularity lines?



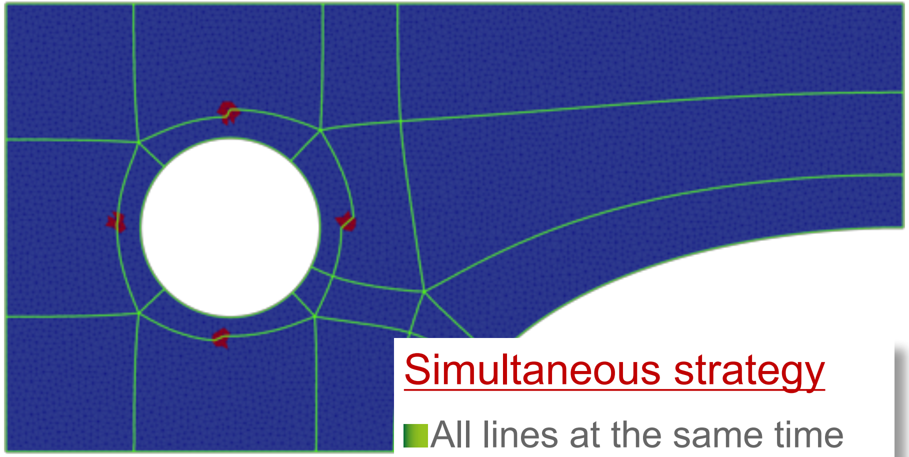
- Define 3/5-indexed **slots** at each **singularity point** (field singularity and non-convex geometric corners)
- Try and connect all of them

Use the frame field geometry to create lines



<u>Sequential strategy</u>

- Single line tracing
- Singularity ball radius
- Heun’s integration

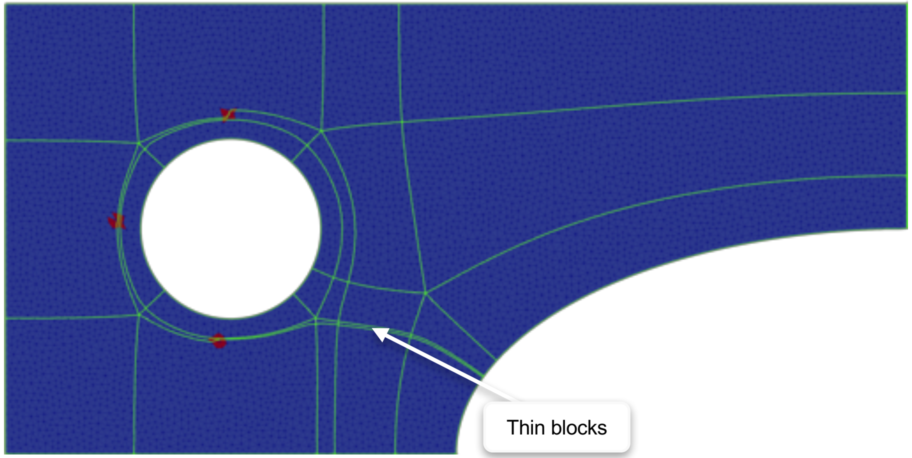


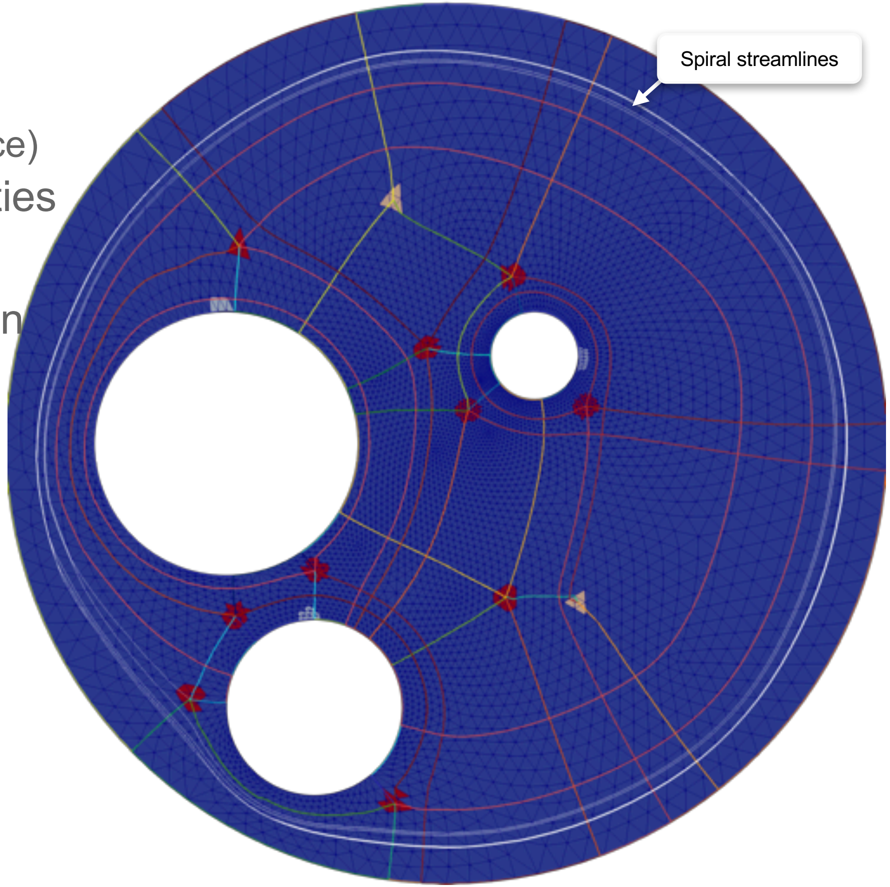
<u>Simultaneous strategy</u>

- All lines at the same time
- Ortho. connecting distance
- RK4 integration

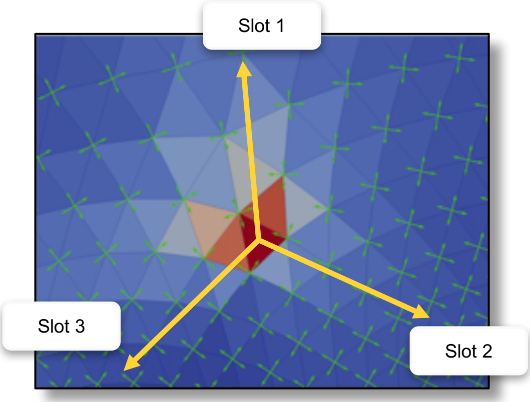
Singularity graph extraction issues

- Strong impact of
  - the mesh resolution
  - Tolerance parameters (sing. ball & connect. distance)
- Streamline tracing error increases near singularities
- Streamlines can spiral infinitely
- Streamline tracing algorithms tend to produce thin blocks



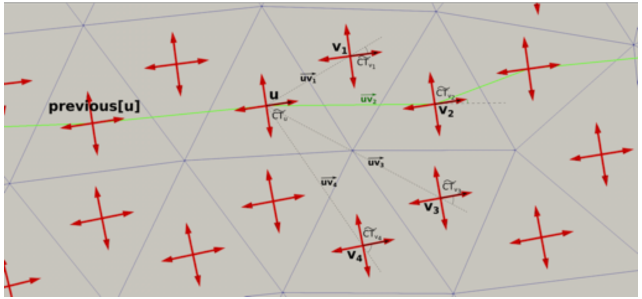


Graph-based tracing



- **Dijkstra** algorithm to compute shortest paths from each slot to the others (boundary edges are possible exit slots)
  - Generate an oriented graph G=(V,E) where
    - V = slots + some boundary points, and
    - E = shortest path from each slot to the others

- Starting from a triangle slot – source
- Walk along triangle centers (u,v0,v1...) visiting adjacent triangles
- Distance as the angle difference between the (previous and
- Get the shortest paths towards the slots of other singularities (or boundary) - targets



- **Integer Linear Programming** for filtering edges of G
  - Minimizing the sum of selected edge weights
  - 1 edge per slot exactly
  - 1 boolean unknown per edge (0-remove, 1-keep)
  - Forbid intersection between edges

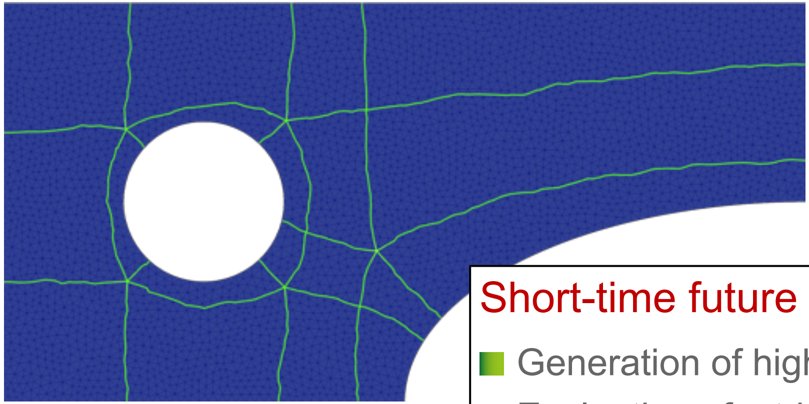
Graph-based tracing

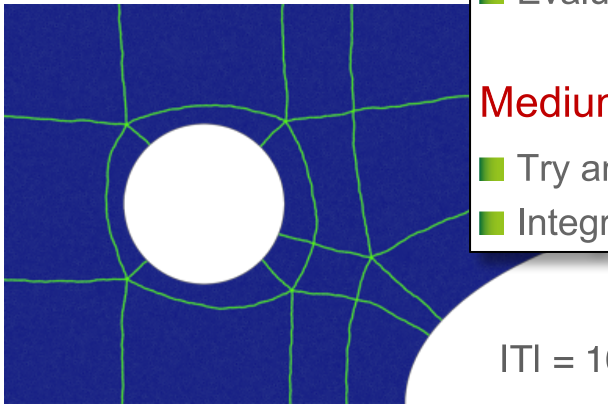
Benefits

- No spiral streamlines
- Improved accuracy with mesh refinement

Drawback

- Computationally more expensive





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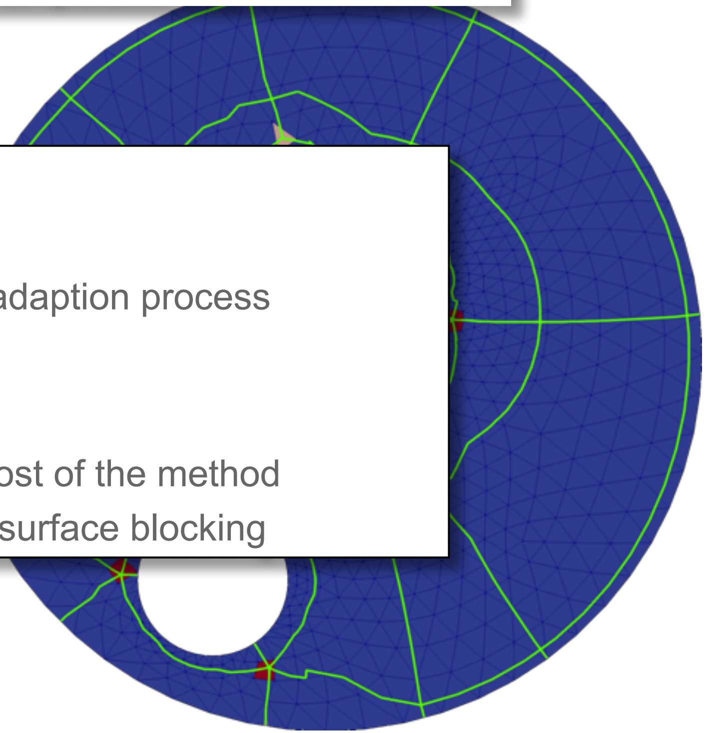


Short-time future work

- Generation of high-order blocks
- Evaluation of a triangular mesh size adaption process

Medium-time future work

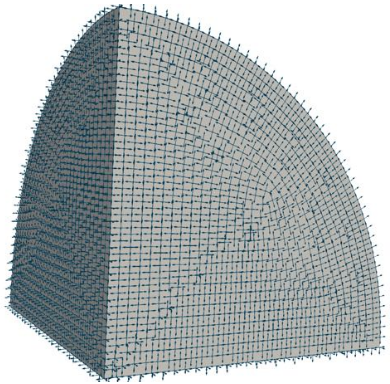
- Try and diminish the computational cost of the method
- Integration to Magix3D for automatic surface blocking

Design of an interactive tool for hexahedral mesh blocking

Simon Calderan's Phd (started in November 2018)

"**Dual-based user-guided hexahedral block generation using frame fields**", Simon Caldéran (CEA), Franck Ledoux (CEA), Guillaume Hutzler, submitted to IMR 2019.

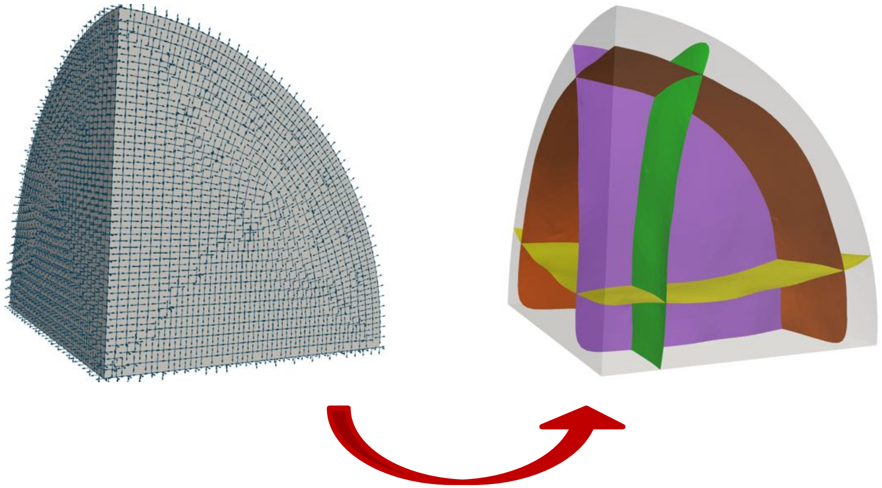
3D Interactive blocking from frame fields



Input: a valid model and frame field

- No 3-5 singularity line
- No jump
- Refined enough

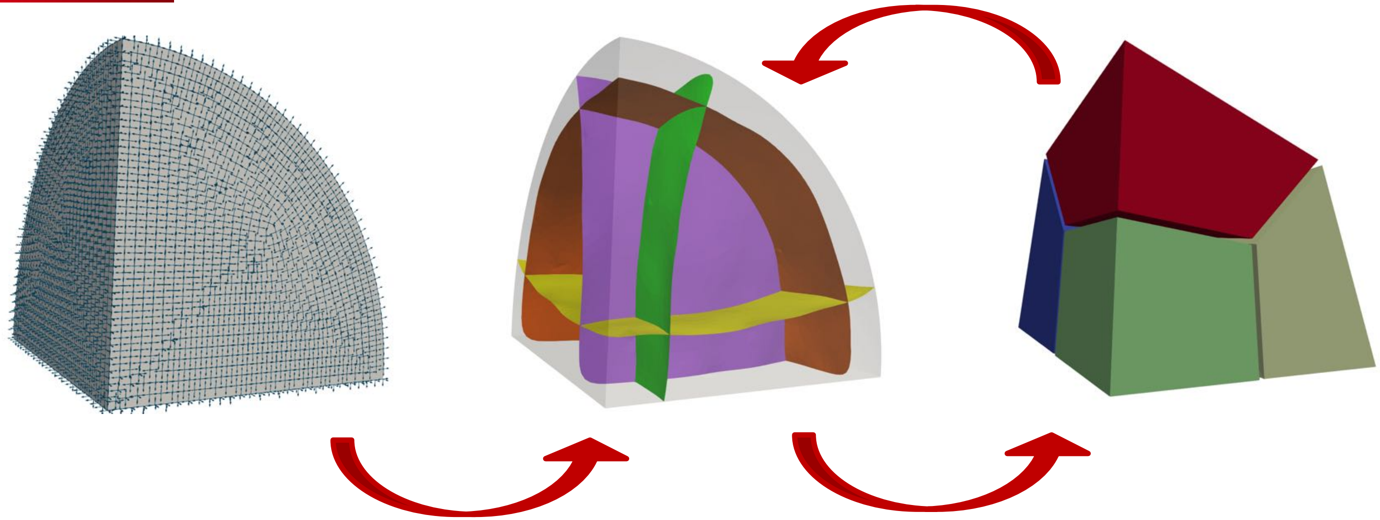
3D Interactive blocking from frame fields



Build dual surfaces

- Select one point and one direction to build a single surface

3D Interactive blocking from frame fields

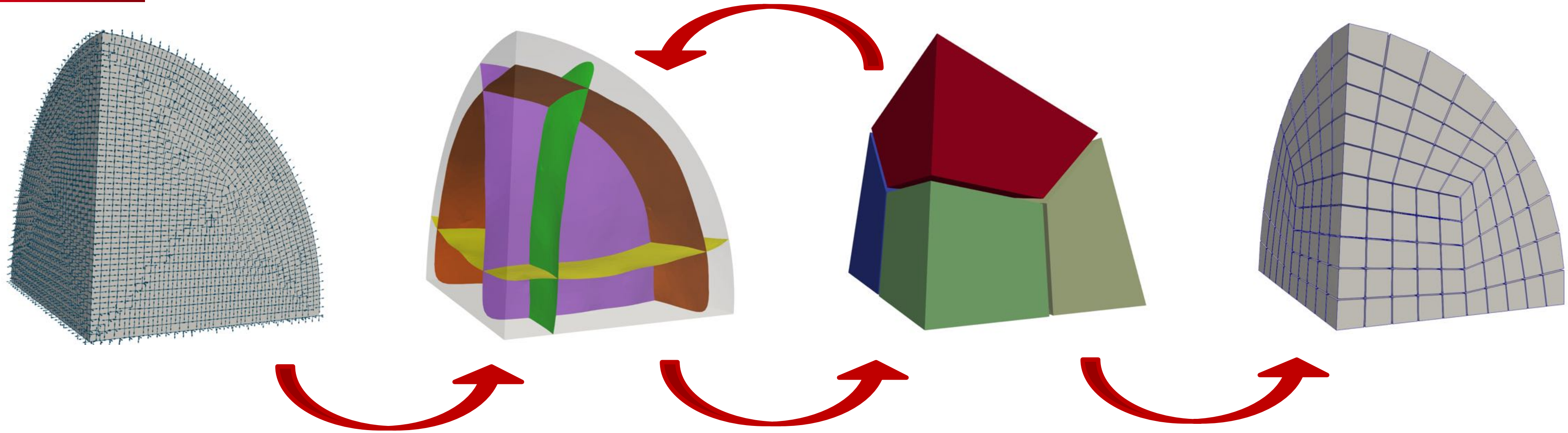


Build dual surfaces

Extract primal blocks

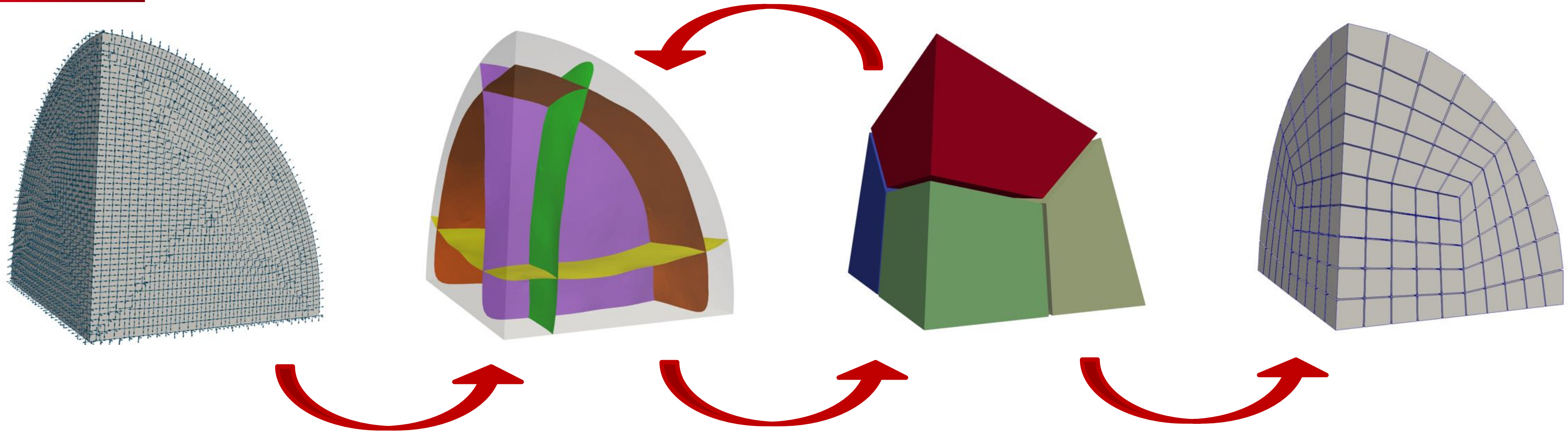
- Check the dual structure validity
- If invalid dual structure, goes back to dual sheet creation

3D Interactive blocking from frame fields



Build dual surfaces   Extract primal blocks   Create final mesh

3D Interactive blocking from frame fields



Build dual surfaces **Extract primal blocks** **Create final mesh**

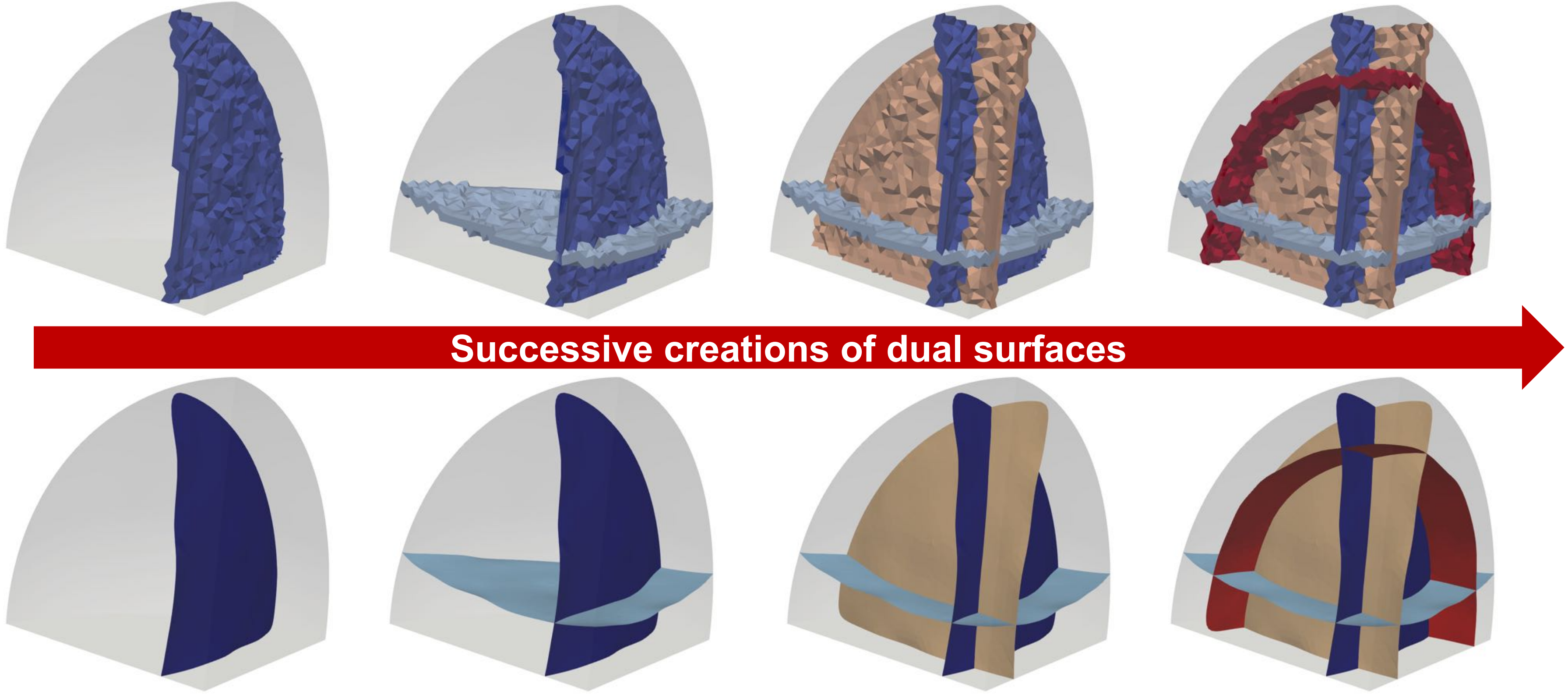
[1] Z. Zheng and R. Wang and S. Gao and Y. Liao and M. Ding, *Dual Surface Based Approach to Block Decomposition of Solid Models*, Proceedinds of the 26th International Meshing Roundtable, 2018.

[2] K. Takayama , *Dual Sheet Meshing: An **Interactive** Approach to Robust Hexahedralization*, Computer Graphics Forum, published by the Eurographics Association, DOI= 10.1111/cgf.13617, 2019.

[3] Marco Livesu and all, *Loopy Cuts: Surface-Field Aware Block Decomposition for Hex-Meshing* , Preprint**,** March 2019.

Dual surface insertion in action

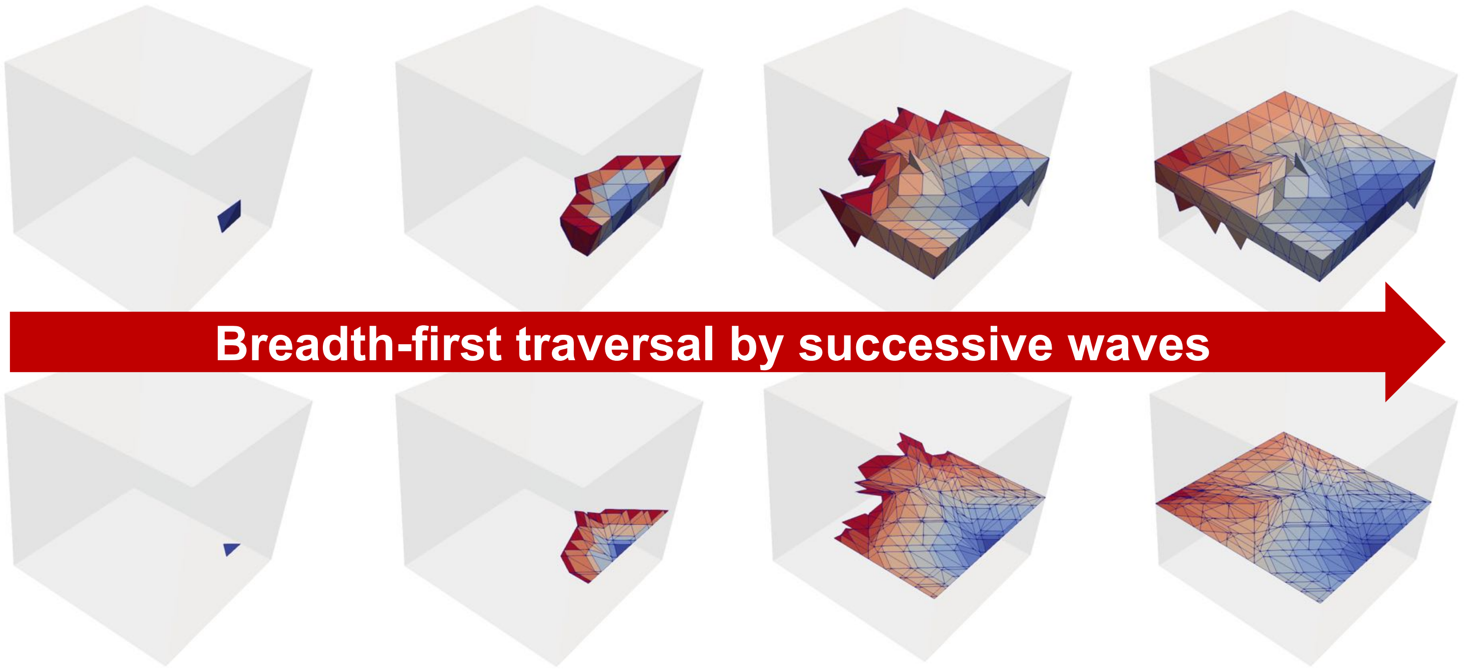
Intersected tetrahedra



Surface-style representation

Dual surface creation

- **Input:** a point (so a tet) and a direction
- Propagation in the *physical* tetrahedral mesh following the frame field along cut edges
- Numerically sensitive → needs control filter near singularity lines



Dual surface creation

- **Input:** a point (so a tet) and a direction
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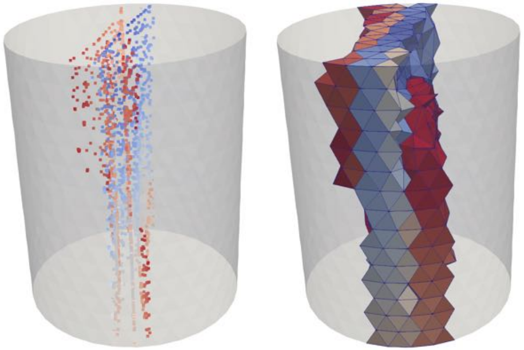
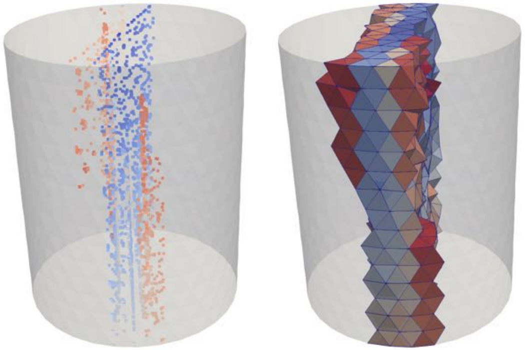
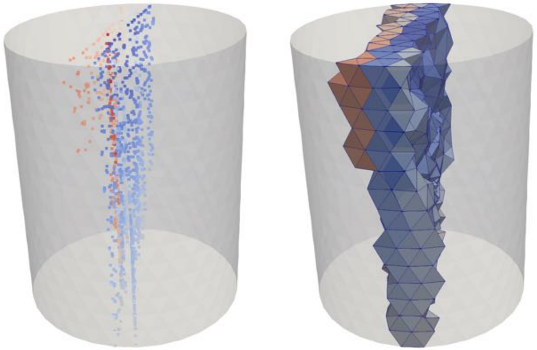


No filter



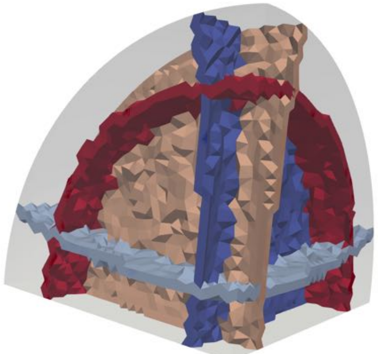
Topological filter
+
Geometric filter (90 degrees)



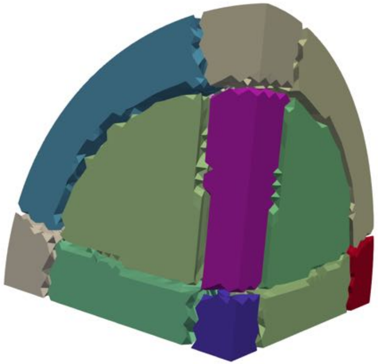
Topological filter
+
Geometric filter (45 degrees)

Dual Structure validation – Rules on dual zones

dual surfaces



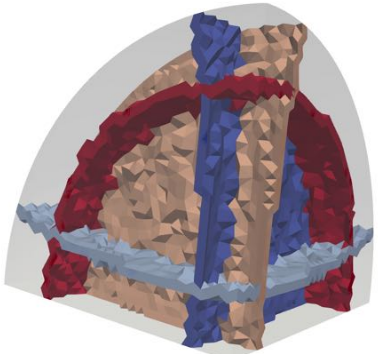
dual surfaces tetrahedra

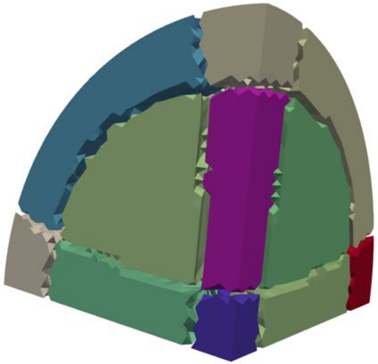


dual zones

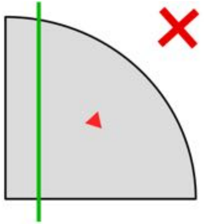
Dual Structure validation – Rules on dual zones

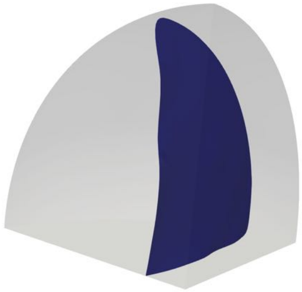

dual surfaces

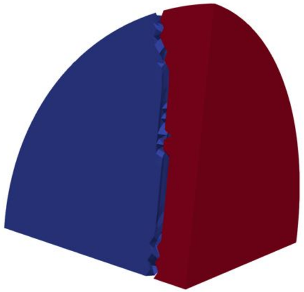

dual surfaces tetrahedra

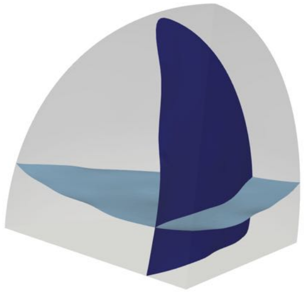

dual zones

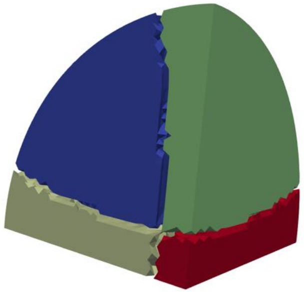
- Only one or two dual surfaces → not a dual hex



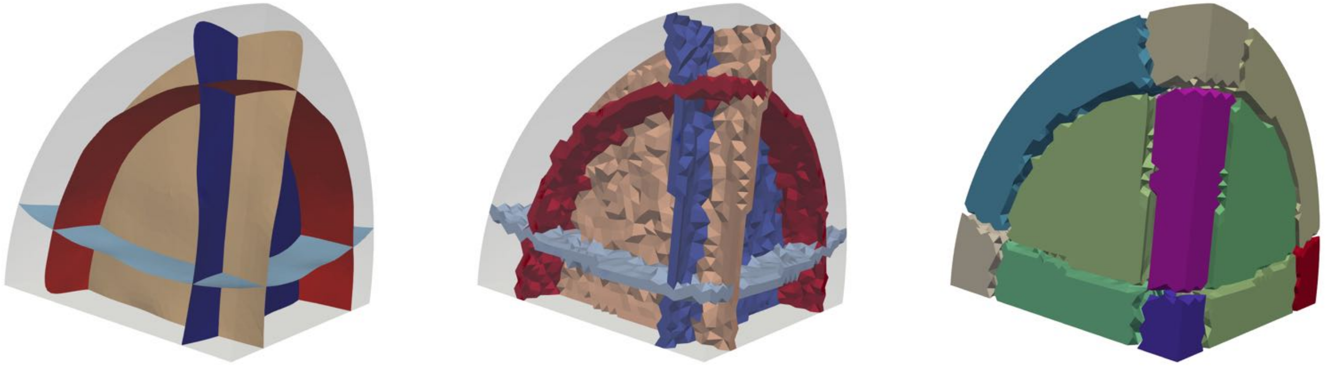






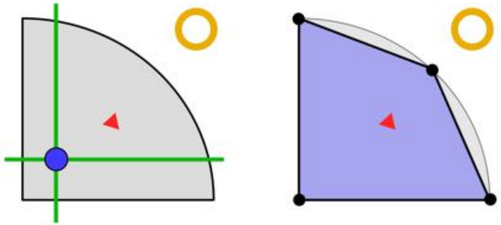


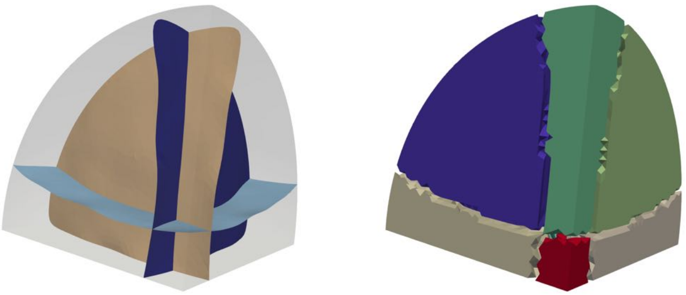
Dual Structure validation – Rules on dual zones



dual surfaces | dual surfaces tetrahedra | dual zones

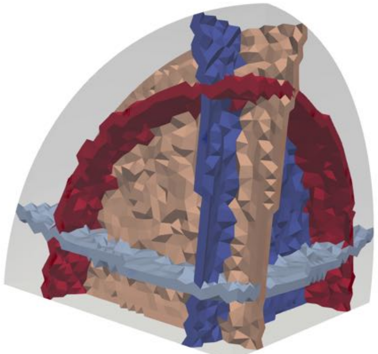
- Only one or two dual surfaces → not a dual hex
- A boundary dual zone can not contain a field singularity



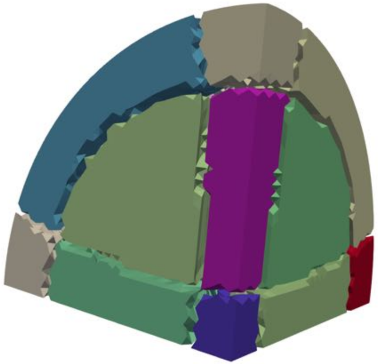


Dual Structure validation – Rules on dual zones

dual surfaces



dual surfaces tetrahedra



dual zones

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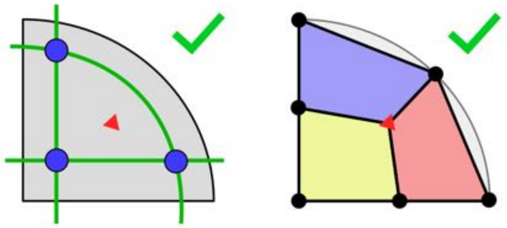
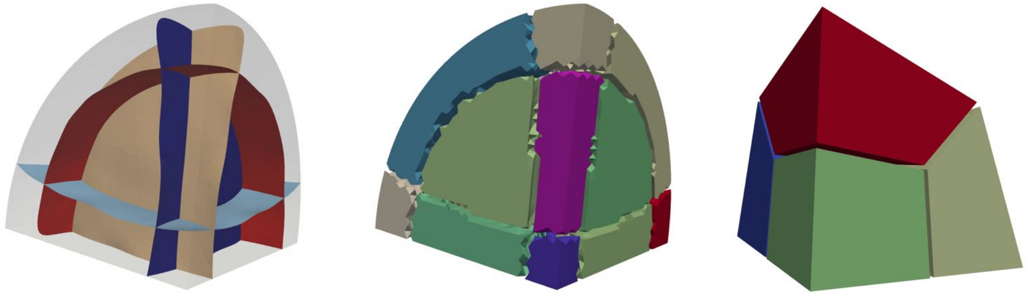
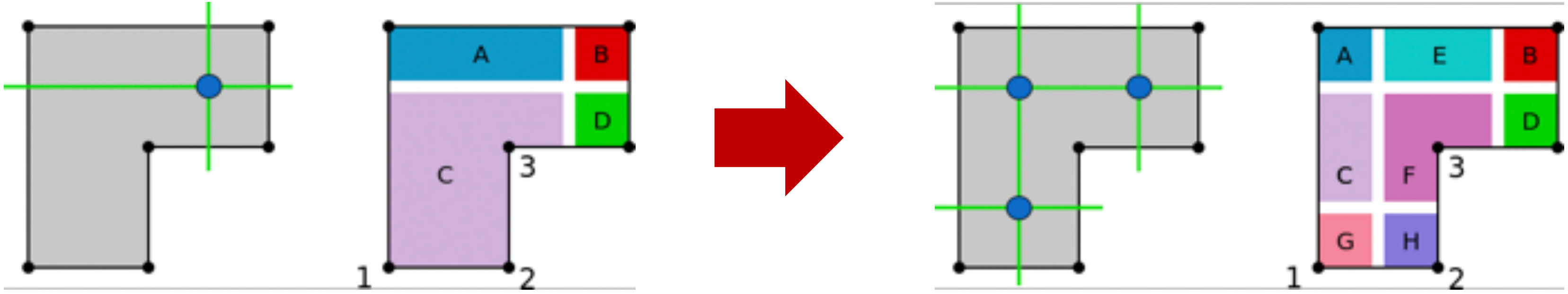
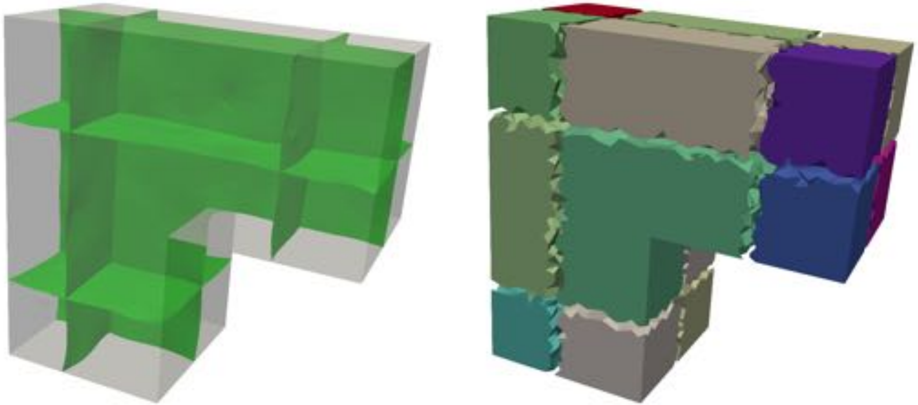




Dual Structure validation – Rules on dual zones

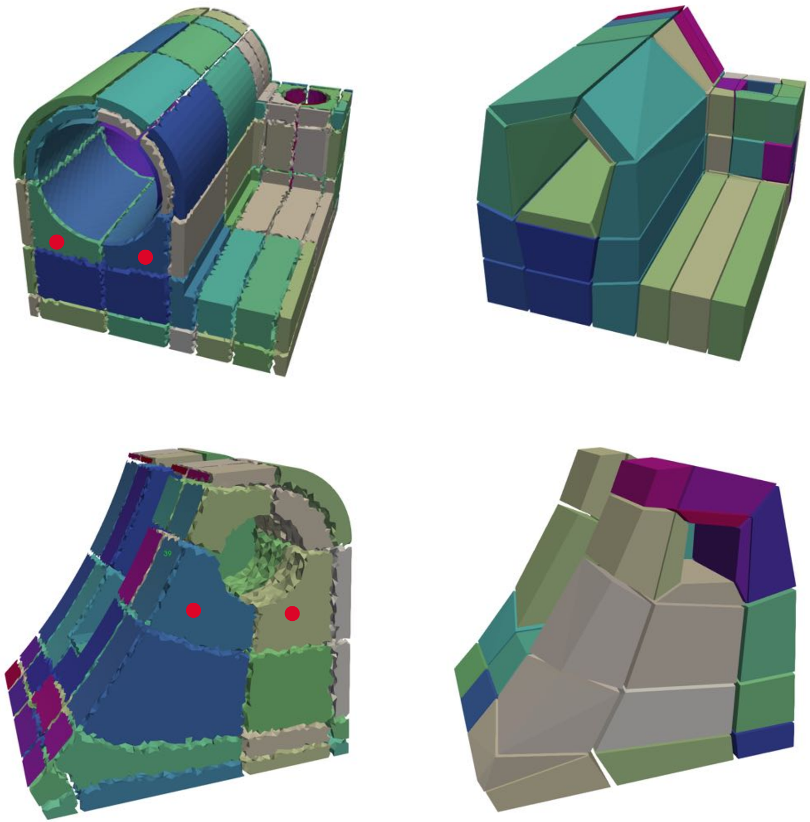


- Only one or two dual surfaces → not a dual hex
- A boundary dual zone can not contain a field singularity or two geometric corners

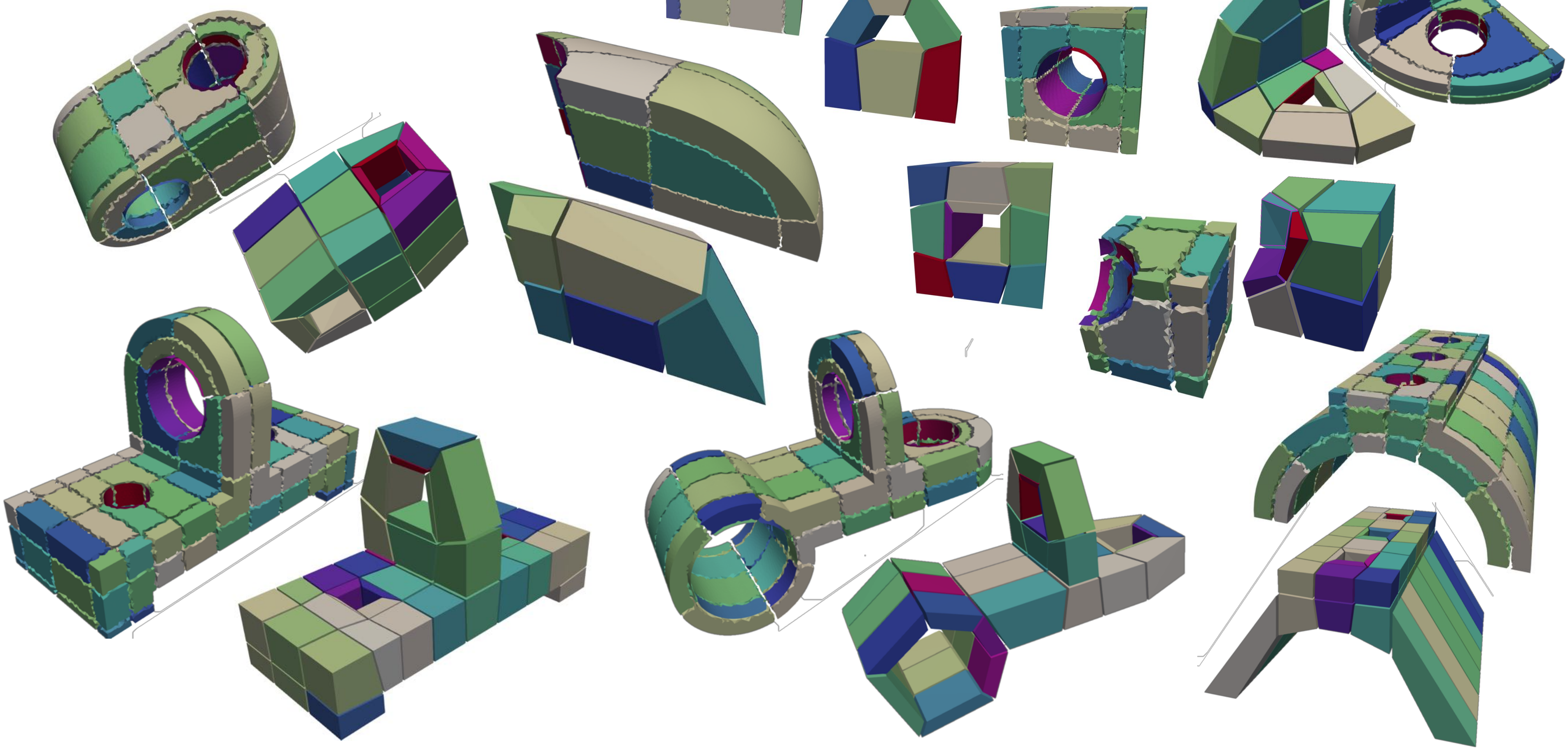


Dual Structure validation – Rules on dual zones

- Only one or two dual surfaces → not a dual hex
- A boundary dual zone can not contain a field singularity or two geometric corners
- A dual zone can not contain two field singularities



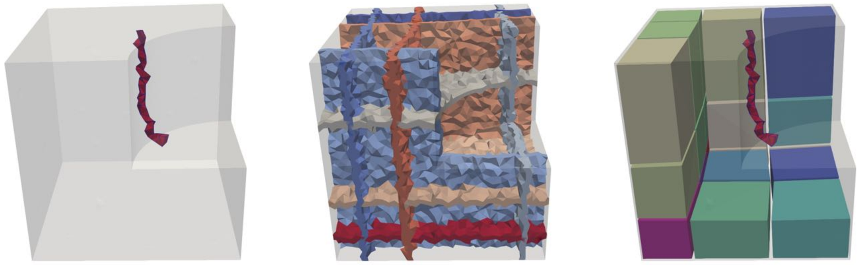
Some first results



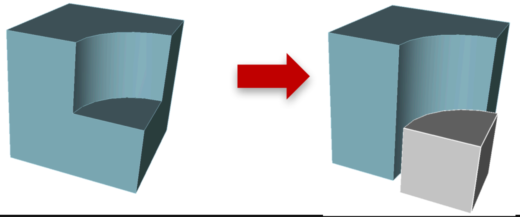
Limitations and future work for interactive 3D blocking

3-5 singularity lines

- Interactive line modification but how to modify the frame field then? See « *Symmetric Moving Frames* », E. Corman, K. Crane, ACM ToG, July 2019 or « *Singularity-constrained octahedral fields for hexahedral meshing* », H. Liu and all, ACM ToG, 2018.

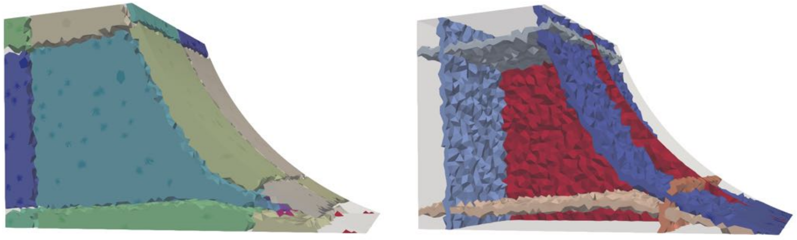


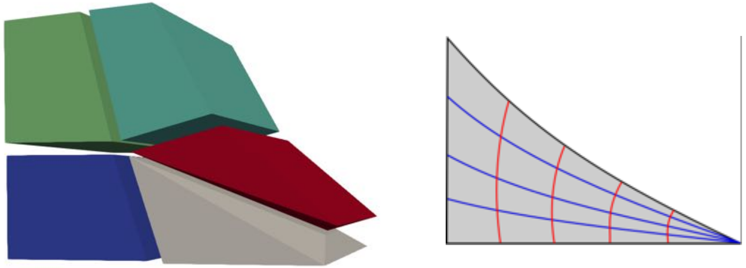
- Model splitting using stable frame fields direction



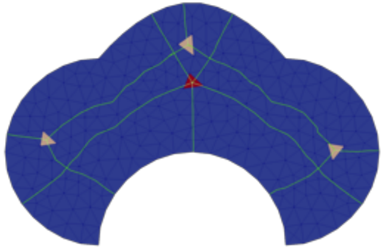
Ski Jump zone

- Pattern insertion via user selection

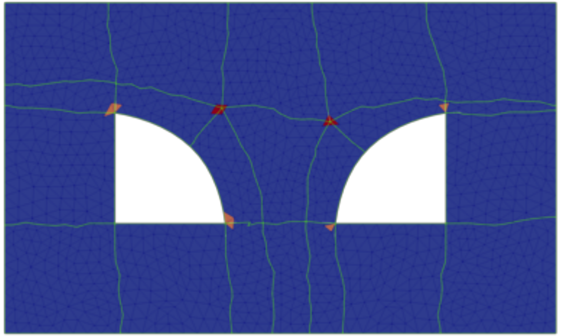




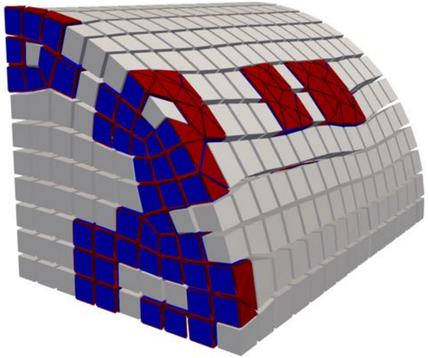
Conclusion about using frame fields for our tools

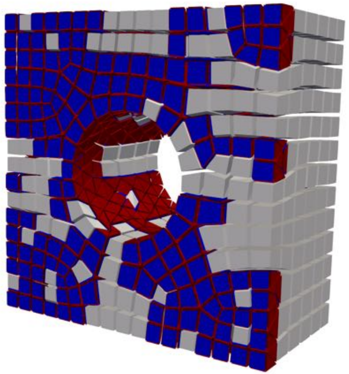


- Quad blocking
  - close to get expected robustness



- Hexahedral-dominant meshing requirements:
  - Constraint some boundaries for assembly models
  - Control hexahedra location
- Hexahedral block meshing
  - Remains a lot of work for automation
  - Interactivity will help us but is not the key





Thank you